New generation of all-optical devices for future communication networks

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ABSTRACT

The need to increase transmission capacity in communication networks is becoming very critical. This task can be accomplished by taking advantage of optical networks where techniques such as DWDM and OTDM are combined with the use of all-optical devices to help eliminate electronic bottlenecks. To fulfill these needs a new class of all-optical devices have been proposed and successfully demonstrated. By taking advantage of the nonlinear dynamics in semiconductor optical amplifiers in combination with optical interferometers new generation of ultrafast all-optical demultiplexers, data regenerators, wavelength, and data format converters have been developed.

Keywords: all optical switching, demultiplexing, TOAD, wavelength conversion, optical routing, MEMS, 2R regeneration

1. INTRODUCTION

As the capacity of a single fiber begins to exceed one Terabit/sec, a new communications bottleneck is emerging at the endpoint of the fibers, where routing is performed to direct the traffic to its destination. Currently, the majority of backbone routers rely upon electronic crossbar switches to route packets. The low speed and scalability of electronic crossbars does not provide sufficient capacity to interconnect multiple optical fibers, each having Terabit/sec throughput. Electronic crossbars rely upon integrated silicon, gallium arsenide, and III-V devices. The switching speed of these devices is determined both by the frequency response of the material and the architecture of the transistors in the switch. While the inherent switching speed of the materials used in integrated electronics today cannot provide the switching bandwidth for the future, large parallel architectures are attempting to beat this physical limit. By fabricating many smaller electronic switches and stacking them in a parallel configuration, it is possible to achieve a high level of connectivity and large aggregate rates approaching 100 Gb/s. However, parallelism can only take the technology so far before the cost of replicating high performance switching hardware dominates the price of the router. In order to build a router capable of handling terabit aggregate bandwidth, the size and cost of the electronics will push the router cost out of the range for current service. It appears that all-optical technology will be the only technology capable of achieving multi-terabit/second communications. For future generations of optical networks to utilize the full bandwidth of optical fiber, we expect data rates on each individual channel in DWDM networks to exceed the practical bit-rate of the driving electronics. To accommodate such high data rates, individual wavelength channels may be composed of modulated, picosecond mode-locked laser pulses from each data source. These new systems will optically aggregate traffic from many users into unique, closely spaced time slots to achieve extremely high data rates on each wavelength by utilizing optical time division multiplexing (OTDM) technologies. Research groups throughout the world have therefore begun exploring OTDM all-optical switching techniques.

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1.1. Photonic switching technology for next generation switches and routers

Despite that fact that electronics is many generations ahead of photonic technology development and has nearly exploited parallelism to its fullest, it appears that optical technology will be the only technology capable of achieving multi-terabit/second switching. The most common optical switching fabric that is currently being integrated into commercial packet switching systems is based upon micro-electro-mechanical systems or MEMS. Simple embodiments of the MEMS technology include movable mirrors that route beams of light according to their destination. For example, the LambdaRouter uses a 256x256 array of movable mirrors to direct light from one fiber to another. Advantages of the MEMS architecture include scalability, low power consumption, low loss, compact size, and protocol transparency. MEMS offer a simple solution to the optical switching problem and avoids the electronic conversion required in standard routers but the applications area is somewhat limited. Since MEMS are inherently mechanical, they are limited in speed. For example, the Lucent LambdaRouter can move its mirrors only on a time scale of 10 ms. While this is appropriate for optical circuit switching and optical layer restoration protection switching, it is not nearly fast enough to support switching on a packet-by-packet basis required by IP routing. The MEMS based switches will most likely interconnect service providers and large cities where continuous traffic streams are established for long periods of time between fixed locations.

Recently, several experimental demonstrations\(^1\),\(^3\),\(^5\),\(^6\),\(^18\) have shown that optical time division multiplexing (OTDM) can meet many of the demanding needs of a high performance switching fabric which include full connectivity, low latency, high aggregate throughput, reliability, and scalability. By using optical TDM, a testbed for a bit-interleaved 100-Gb/s switched interconnect has been constructed based upon a broadcast star architecture\(^18\).

Unique to this network architecture is a highly scalable, novel node design that provides average inter-channel switching latency equal to the single channel bit period of 1.6 ns. This architecture is faster and more scalable than electronic crossbars and can be used as a switching fabric in the backbone of an enterprise switch or backbone router.

Figure 1 shows the network and novel node architecture. The two key optical components of the node are the fast time slot tuner\(^10\) and an ultrafast all-optical demultiplexer called the “TOAD” \(^2\), which will be discussed in more detail below. A network interface card (NIC) sends electronic NRZ data at the single channel bit-rate, \(B\), and control bits to a controller board specially designed to operate the two time slot tuners on the optical clock and data lines. The time slot tuners in the node are used in the transmitter to send modulated data into a given time slot within the optical TDM frame and in the receiver to align the optical clock with a given time slot for optical demultiplexing using the TOAD. To achieve global synchronization, picosecond pulses from a single fiber mode-locked laser source are amplified and distributed to the individual nodes via 1xN splitters. After node data modulation and time slot selection, the data are multiplexed by precision fiber delays feeding an NxN star coupler. The high bandwidth optical TDM frame is broadcast to all nodes in the network. The overall structure of the aggregated OTDM frame is determined by the time slot tuners used in the network nodes. This architecture represents a practical and scalable alternative to electronically switched backplanes. In addition to single-channel access, advanced services such as multicasting using the same optical subsystems and components have been demonstrated\(^11\). If OC-24 (\(B = 1.24416\) GHz) is chosen as the single channel data rate and 10-GHz intermediate processing electronics are used, an 80-Gb/s interconnect with an average rapid inter-channel switching speed of 800 ps is feasible. To implement this architecture ultra high speed all-optical devices for data processing are needed.
2. INTERFEROMETRIC DEVICES FOR ALL-OPTICAL PROCESSING

Interferometric devices for ultra high speed all-optical processing have been of great interest to the research community for some time and gained momentum in the research community with the development of nonlinear optical loop mirrors (NOLMs). These devices, which simply consist of a 2x2 coupler and a long loop of fiber formed by joining the two fibers of one of the coupler’s ends together, rely upon weak nonlinear interactions between a control and a signal pulse as they both co-propagate around the loop. If the nonlinear interaction is sufficiently large, a phase shift in the signal pulse propagating with the control pulse can be induced with respect to the counter-propagating signal pulse which does not travel with the control pulse. The change in phase alters the interference condition at the base of the loop when the signals recombine at the coupler and switches the signal to the output port. Signals entering the loop in the absence of the control pulse, do not experience an appreciable phase change and are reflected back toward the source.

Finding a technique to reduce the control pulse energy and fiber lengths required in NOLMs relied upon using a nonlinear material other than fiber. Many groundbreaking experiments with semiconductor optical amplifiers (SOAs) inserted into the loop demonstrated that low energy optical pulses could change the gain of the amplifiers sufficiently to produce significant phase shifts in subsequent pulses passing through the amplifier. Additionally, the temporal onset of the phase shift was nearly as fast as the rising edge of the control pulse. Unlike non-resonant fiber nonlinearity, however, this resonant, interband nonlinearity in the semiconductor material has a long relaxation time (100 to 500 ps). Efforts were soon underway to form a new class of switching devices based upon the efficient resonant nonlinearity in SOAs to induce a differential phase change between the two signal pulses counter-propagating in the fiber loop. The first device developed was known as a semiconductor laser amplifier in a loop mirror (SLALOM) and was used to investigate “contrast enhancement and optical correlation”.

Although the rising edge of the temporal switching window was a few picoseconds, the window’s falling edge depended upon the gain recovery time of the SOA which was approximately 400 ps. Another innovation to produce picosecond switching windows with SOAs was an architectural realization. It was discovered that the temporal duration of the window could be controlled by changing the asymmetric placement of the SOA. Due to the dynamics of this configuration, the switching window actually closes earlier than the recovery time of the SOA as the SOA is moved closer to the midpoint. Figure 2a shows a schematic diagram of this device known as a Terahertz Optical Asymmetric Demultiplexer (TOAD).

![Figure 2. Schematic diagram of ultrafast all-optical demultiplexers. a) The TOAD; b) Two cascaded TOADs.](image)

In the absence of a control pulse, data pulses enter the fiber loop, pass through the SOA at different times as they counter-propagate around the loop, and recombine interferometrically at the coupler. Since both pulses see the same medium as they propagate around the loop, the data is reflected back toward the source. In the presence of the control pulse, switching can occur. When a control pulse is injected into the loop, it saturates the SOA and changes its index of refraction. As a result, a differential phase shift can be achieved between the two counter-propagating data pulses to switch the data pulses to the output port. Only the pulses that co-propagate with and travel just behind the control pulse by up to twice the optical path length of the SOA offset are switched to the output port. All subsequent pulses will either see an unsaturated amplifier or a slowly recovering amplifier and will be reflected back toward the source. A polarization or wavelength filter is used at the output to reject the control and pass the switched data signal. The temporal duration of the switching window is determined by the offset of the SOA, $\Delta x$, from the center position of the loop. As this offset is reduced, the switching window size decreases. The size of the nominal switching window duration, $\tau_{win}$, is related to the offset position by $\tau_{win} = 2\Delta x / c_{fiber}$ (where $c_{fiber}$ is the speed of light in fiber).
precisely controlling the offset position of the SOA, very short switching window SW was achieved allowing demultiplexing of a single channel from a 250-Gb/s data stream. The practical control and data pulse energy requirements make it well-suited for typical communication signal powers (< 1 pJ). As the size of the device only depends upon the SOA length and offset from the center position in the loop, compact TOADS based upon discrete components have been constructed with very short loop lengths (less than 0.5 meter).

A characteristic of the TOAD switching window is that the rising and falling edges have different slope. The location of each edge is determined by the side of the fiber loop that the SOA is placed, with respect to the control port (see the individual shapes of \( SW_A(t) \) and \( SW_B(t) \) in Figure 2b). This causes that the transfer function \( SW(t) \) of the TOAD is asymmetric. However, this issue can be resolved by using two TOADS instead of one. By cascading two TOADS as seen in Figure 2b with a time shift of \( \delta \) between the TOAD’s windows, the overall transfer function referred to as \( \text{Cascade}(t, \delta) \) becomes the product of the two constituent ones, \( SW_A(t) \) and \( SW_B(t) \): \( \text{Cascade}(t, \delta) = SW_A(t) \times SW_B(t - \delta) \). If the switching windows are “placed” such that the sharp edge of each overlaps the sharp edge of the other (see inset in Figure 2b) it will result in a smaller symmetric switching window with the size limited mainly by the optical pulse width of the control signal. It has been shown that two cascaded TOADS each having asymmetric switching windows \( SW_A = SW_B = 8 \text{ ps wide} \) will produce symmetric switching window as short as 2.9 ps.

The TOAD is robust to temperature variations and can be reliably operated without stabilization as data signals propagating in both directions around the loop experience the same effective medium. With the successful development of all-optical demultiplexing, many new techniques have been used to enhance the performance of these devices. As the optical switching function is based upon gain saturation in an SOA, the repetition rate of the demultiplexing operation is somewhat limited by the recovery time of the amplifier. Novel optical biasing techniques using CW light have significantly reduced the recovery time. It has been estimated that these techniques may enable the optical switch to function at repetition rates approaching 100 GHz. Other demonstrations have shown that the TOAD can be successfully used to demultiplex many wavelengths simultaneously from an aggregated OTDM/WDM data stream.

**Gain-Transparent SOA-Switch (GAT-Switch)** Dual wavelength operation of the TOAD/SLALOM configuration known as the Gain-Transparent SOA-Switch (GAT SOA-Switch) has been proposed and demonstrated. This device (Figure 3) uses a data signal at a longer wavelength (1.55 \( \mu \text{m} \)) than the control signal (1.3 \( \mu \text{m} \)) so that it is far from the band edge of the optical amplifier. The technique enhances the signal-to-noise ratio of the device and can improve the switching contrast at the output. The GT SOA-switch has been successfully applied as an add/drop multiplexer and to simultaneous demultiplexing of several wavelength channels from an OTDM/WDM data stream. On other hand dual wavelength operation of such a switch could be to difficult to implement in the real optical network.

**Ultrafast Nonlinear Interferometer (UNI)**, developed at MIT Lincoln Labs, is another ultrafast all-optical OTDM switch using an SOA as the nonlinear element in a single-arm interferometer (Figure 4). By using a long length of Birefringent (PM) Fiber to separate orthogonally polarized components of data pulses in time, a control pulse can be introduced precisely between the components of a data pulse. When these components pass through the SOA, only the data pulse whose components are separated by the control pulse will experience a differential phase change. As a result, when the pulses are realigned by another long length of PM fiber, the components will interfere with each other. Only the pulse which experiences the differential phase change induced by the control pulse will be passed to the Output through the Polarization Filter (PM Filter). Although the TOAD/SLALOM and the UNI share several characteristics, the integratability and practicality of the UNI are limited by the long lengths of PM fiber needed to induce the polarization walk-off. The switching window of the UNI is determined primarily by the birefringence of the PM fiber used to separate orthogonally polarized components of the data pulses in time. Enough walk-off is required to insert a control pulse between these two pulses. At a minimum, the walk-off should be longer than the control pulse width. Like any other SOA based switch, the UNI is limited by intraband carrier dynamics and carrier heating. Switching windows of about 1 ps can be expected. The switching repetition rate can be limited by the carrier recombination time in the SOA. However, 100 GHz repetition
rates for bitwise logic functions have been reported. As with any SOA-based switch, the UNI also has a noise background added to the switched signal due to spontaneous emission from the SOA. Noise figures in the range of 6 dB are typical for SOAs. Filtering and other techniques can be used to reduce the accumulation of noise in the signal for cascaded devices. Since the UNI requires at least 15 m of PM fiber to produce the switching window, it is not likely that it will be easy to integrate. Since the UNI is dependent upon birefringence to achieve switching, the system must use polarization control throughout the network to maintain reliability.

**All-Optical Wavelength Conversion with 2R-regeneration.** To prevent blocking, wavelength conversion is one of the key functions which must be performed in existing DWDM optical networks. In current optical networks in order to perform conversion from wavelength \( \lambda_1 \) to wavelength \( \lambda_2 \), an optical signal at \( \lambda_1 \) must be first detected by a photoreceiver, then converted into an RF signal. This RF signal is now used to modulate a cw DFB laser to generate the required data at the new wavelength \( \lambda_2 \). This process is relatively slow and creates electronic bottlenecks in existing systems. This can be avoided if wavelength conversion is done all-optically. One device capable of such an operation is called TOAD Based Wavelength Converter. Schematic diagram of the device is in figure 5. This converter exploits phase modulation of the SOA placed inside of a Sagnac interferometer. Its operation is based on TOAD principle which already has been explain in this paper elsewhere. In this case however, incoming data signal at \( \lambda_1 \) serves as a control signal for the TOAD based wavelength converter. Converter imprints data carried at \( \lambda_1 \) on another wavelength \( \lambda_2 \) which travels inside of the interferometer through the SOA (\( \lambda_2 \) is generated by tunable cw DFB laser). At the end, the data of desired wavelength \( \lambda_2 \) will exit wavelength converter’s output port.

It has been demonstrated that this device can operate error free with RZ or NRZ data formats at OC-192 rates. To achieve this performance the SOA offset \( \Delta \) (see figure 5) was adjusted to satisfy following condition:

\[
\tau_{\text{min}} = 2\Delta / c_{\text{fiber}} = 1 / B_{\text{OC-192}} (B = 9.95328 \, \text{GHz}).
\]

Another device capable of performing all-optical wavelength conversion has been developed by Alcatel. It is called Integrated All-Optical Wavelength Converter 1901 ICM. Figure 6 is a schematic diagram of the device. This converter exploits cross-phase modulation in an integrated Mach-Zehnder (MZ) interferometer based on an all-active MZ-SOA structure. An input modulated signal at a wavelength \( \lambda_1 \) modulates the carrier density in the SOA inside of the interferometer, producing a modulation of its refractive index. This in turn leads to phase modulation of an injected cw beam at the desired output wavelength \( \lambda_2 \), which is converted to amplitude modulation via the MZ interferometer. The signal data pattern is therefore transferred to the new desired wavelength \( \lambda_2 \).

Both devices, TOAD based wavelength converter as well as Alcatel 1901 ICM, have nonlinear transfer function which allows both enhancement of the signal extinction ratio and compression of the optical noise amplitude. In addition, at the output of the converter the signal emerges re-amplified and re-shaped. This property is called 2R regeneration.

### 3. CONCLUSIONS

Although electronics has made great strides toward satisfying the switching bandwidth in communication networks, it does not appear that electronic devices will reach future required speeds even with the highest degree of parallelism. We have presented approaches exploiting on all-optical switching technology based upon SOA nonlinearities. Due to the low optical energy requirements, we believe these devices represent a practical approach to future, high-speed systems employing all-optical signal processing. Successful demonstrations of optical demultiplexing, packet routing, simultaneous wavelength conversion and data regeneration are some of the functions that these devices can perform. Although some optical switch architectures have already been integrated, the future commercial potential of these devices depends upon further progress toward cost-effective photonic integration and packaging techniques. Pushing the optical switching bandwidth to 1 THz and beyond continues to be a challenging area for future research. Further exploration of semiconductor optical nonlinearities with ultrafast response times (<1 ps) may enhance the switching
speed of these interferometric devices or yield an entirely new class of all-optical switches capable of meeting the demand for bandwidth in future optical networks.

REFERENCES