High Data Rate Coherent Optical Slot Switched Networks: A Practical and Technological Perspective

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ABSTRACT

We review several node architectures for optical slot switching ring networks, which can be used in metropolitan or datacenter applications, and compare them for their networking aspects. The dimensioning, quality of service, latency, and protection issues are discussed for the different approaches. The main devices, i.e. fast wavelength-tunable laser, burst-mode coherent receiver (which is required to enable high data rate transmission at 100 Gb/s and above), and a slot blocker for improved wavelength usage efficiency are described, and available technologies for each key building block are reviewed.

INTRODUCTION

Optical packet switching refers to any technology that brings into optical communications the packet switching paradigm, which is well known in electronics. Optical packet switching generally relies on the following principles: opto-electronic conversions (and processing) occur only at source and destination nodes, while intermediate nodes switch data at a short (nanosecond to millisecond) granularity, using a so called all-optical or "transparent" switching fabric. The reduction in opto-electronic conversions translates into energy savings, and facilitates network upgrades, since transparent switching fabrics can often be made independent of the data rate of the signals used in the network. The switching of data with sub-wavelength granularity enables statistical multiplexing, i.e. the sharing of the transport medium between several data flows. Packet switching is also well adapted to the increasing amount of Internet protocol (IP) traffic (as opposed to voice circuits) carried in telecommunication networks. Optical slot switching is a version of optical packet switching, where all switched entities are slots of the same duration. Industrial research on optical packet switching has recently focused on optical slotted switched (OSS) rings [1–4], as depicted in Fig. 1, in the context of metropolitan-area (metro) networks. Topologies more complex than rings, such as meshes and interconnected optical rings, can also be built.

Optical slot switching enables sub-wavelength networking directly at the optical layer, without resorting to costly intermediate opto-electronic conversions. The same transponder (a combination of an emitter and of a receiver) can be used to transmit (or receive) data to (from) several destinations (sources), as opposed to traditional circuit-switched networks, which establish a static connection between a source and a destination, whether this connection is fully used or not. Sub-wavelength networking is relevant for instance in next-generation optical mobile backhaul networks, where nearby base stations cooperate to cancel interferences (enabled by coordinated multipoint technology) and need direct, low-latency communication at data rates well below typical channel rates of 10 Gb/s or more [5]. In addition, optical slot switching networks enable highly dynamic adaptation to traffic variations. Those features are especially useful in metro networks, which rely today either on static circuit-switched networks or power-hungry all-electronic switches; and in datacenters, which again today rely on all-electronic switches that can easily adapt to the highly variable and unpredictable traffic, at the cost of high power consumption [6].

Even though the components and subsystems presented in this article are suitable for ring and mesh networks, we limit the architecture discussion to *slotted rings*. Optical packet switching in *meshed* networks introduces additional challenges, mostly related to ranging and scheduling of the optical packets. Asynchronous and variable-size IP packets that can be as small as 46 bytes are too short at high data rates (10 Gb/s in access networks, 100 Gb/s and above in core transport networks) to be efficiently switched with current optical technologies. To resolve this problem, packets are first aggregated at the network edges into "bursts" (here, slots) of data, which are sufficiently long to be compatible with the switching times of optical elements [7]. Contention, which occurs when several nodes want

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to send packets to the same node simultaneously, can be resolved by scheduling when the slots are sent into the ring or mesh network [8], or by having the capability of electronic buffering at intermediate routing nodes [9].

In the past few years Alcatel-Lucent Bell Labs has proposed several node architectures for high speed OSS rings [1, 2] using coherent signaling for high data rate transmission of 100 Gb/s per channel and above, targeted to metro or datacenter networks; data transmission is all-optical, but control and scheduling are performed in the electronic domain. This paper reviews the formerly proposed node architectures and compares them for key networking aspects. Coherent OSS rings require complex components, which has so far hindered their development and deployment. We describe those components and subsystems and show how we resolved some of the key technological challenges. In addition, we show how the key components could be integrated thanks to technologies such as silicon photonics, so that node cost could be reduced and made compatible with the metro or datacenter segments. Finally, we draw brief conclusions.

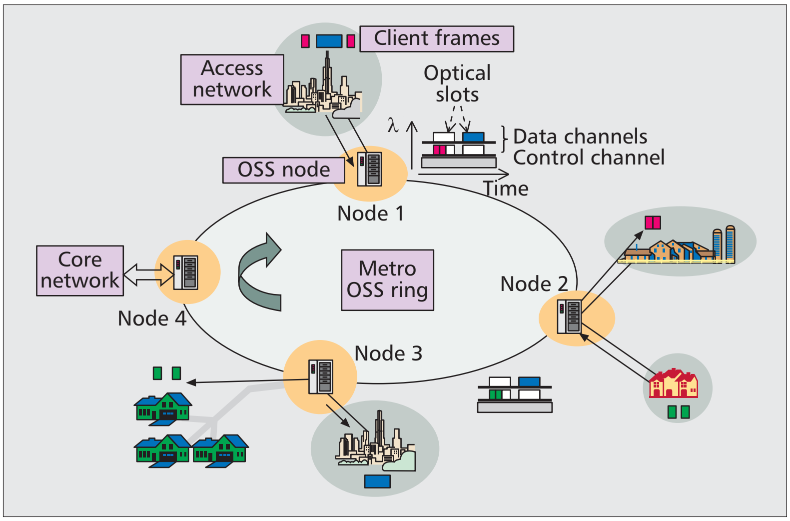

Figure 1. A sample optical slot switching network with two data channels and a control channel. Node 1 encapsulates a blue frame (coming from an access network) in a slot inserted on the first (top) data channel with destination node 3, and two red frames in a slot inserted on the second (bottom) data channel with destination node 2. Node 2 receives the slot containing the red frames and inserts a new slot containing green frames with destination node 3. Node 3 extracts the slots containing the blue and green frames.

NODE ARCHITECTURES

A typical OSS ring network is depicted in Fig. 1. Data is encapsulated in fixed-duration slots, converted to a wavelength division multiplexed (WDM) optical signal, sent onto a ring network, where it transits transparently through the intermediate nodes, and is converted back to the electronic domain at the destination only. In addition, a control channel that is demodulated and electronically processed at every node carries the headers of each synchronous WDM slot. Those headers contain routing information such as the source and destination node for each WDM slot. The control channel is also used to carry a clock to all nodes and ensure synchronous operation of the ring.

Figures 2a–c present three OSS node architectures (OSSv1 in Fig. 2a, OSSv2 in Fig. 2b, and OSSv3 in Fig. 2c), which all rely on the same basic key blocks:

- An optical blocker, implemented either as a static wavelength blocker (for instance, using a wavelength selective switch (WSS)) in OSSv1, or a dynamic slot blocker that can physically erase slots after they are received so as to reuse the fiber capacity in OSSv2 and OSSv3. Hence, with OSSv2 and OSSv3, the same wavelength can be shared by several transponders.
- "Burst-mode" receivers, which are capable of receiving bursts of data (duration: a few microseconds) separated by short guard intervals (duration: well below 1 microsecond)
- Fast tunable lasers, which can change their emission wavelength on a per-slot basis, are used as local oscillators to make the coherent receivers fast wavelength-tunable. Fast tunable lasers are also used in the *transmitters* of OSSv3.

In addition, amplification may be provided by standard optical amplifiers (EDFA). The utilization of specialized burst-mode EDFA with complex gain control electronics can be avoided by sending continuous streams of data in OSSv1 and keeping the guard intervals short (a few tens or hundreds of nanoseconds) in OSSv2 and OSSv3. Since no data can be transmitted during the guard intervals, slots have to be several microseconds long and may encapsulate several typical-sized (1500 bytes) client packets at data rates of 100 Gb/s and beyond. The guard interval has to be kept sufficiently short to avoid interaction with the EDFA automated gain control mechanisms and also to reduce wasted capacity, since no useful data is sent during the guard interval; at the same time the guard interval should be sufficiently long to allow the tuning of the switching elements (fast tunable lasers, slot

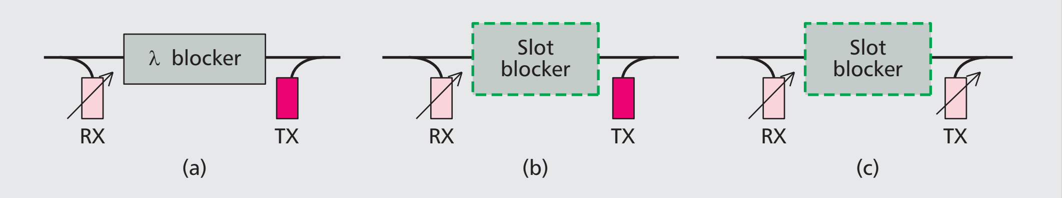

Figure 2. Optical slot switching node architectures: (a) OSSv1, (b) OSSv2, (c) OSSv3. An arrow indicates that the component contains a fast wavelength tunable laser, whereas the dark color TX block with no arrow is a fixed-wavelength laser.

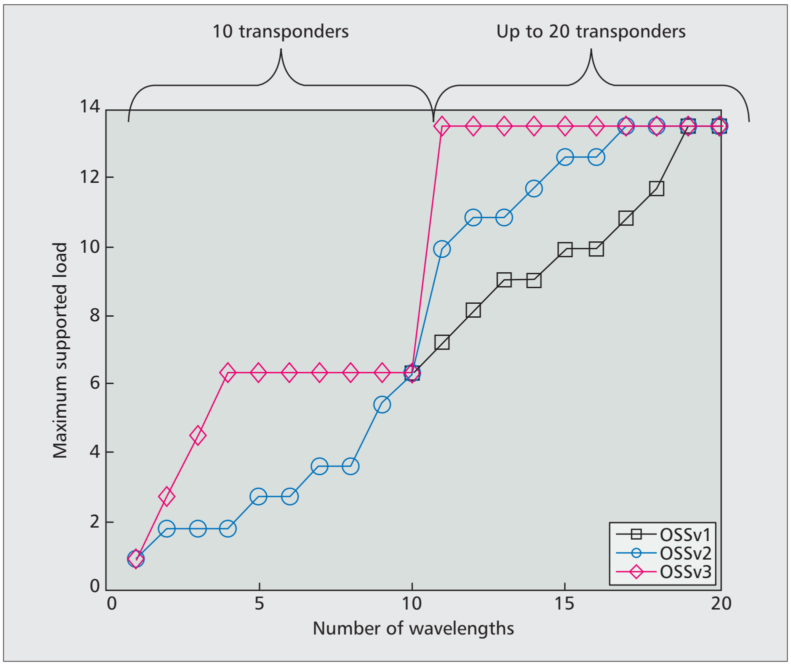

Figure 3. Comparison of the maximum supported load by the three proposed OSS nodes architectures in a 10-node unidirectional ring network, for a given amount of deployed resources (transponders and wavelengths). The supported load is normalized by the channel data rate. OSS v1 requires a minimum of 10 wavelengths for full connectivity.

blocker) when they change state.

In OSSv1, "colored" emitters transmit on a predefined/static wavelength. Light from such an emitter enters the network after a wavelength blocker (Fig. 2a), which statically blocks incoming wavelength(s) to allow emission by the node at those wavelengths. In OSSv2, emitters are also colored but can be turned on or off on a slot-by-slot basis to allow the optical blocker, which is also reconfigurable at the slot granularity, to selectively erase slots. The node can re-use the capacity freed by the slot blocker in order to send new data onto the ring. OSSv3 uses both wavelength-tunable emitters and receivers (each leveraging a fast-tunable laser), in addition to a slot blocker. The OSS node architectures are increasingly flexible and dynamic, but also more complex and costly. The benefits of the flexibility in terms of maximum supported load in the network will be investigated.

NETWORKING ASPECTS

DIMENSIONING

In order to compare the three optical slot switching networks introduced in Fig. 2, we devised a dimensioning heuristic algorithm for each OSS variation. Given a traffic demand matrix, dimensioning gives the number of transponders and wavelengths required to carry the demand. Minimization of the number of transponders can be done by allocating as many transponders as required by the traffic matrix (this is the same number for all OSS flavors) and dedicating a separate wavelength for each transponder. Note that the utilization of slot blockers enables wavelength sharing by several transponders with OSSv2 and OSSv3. Wavelength sharing decreases the number of required wavelengths, which in turn also reduces the network cost (since OSSv2 and OSSv3 require one gate per channel on every node), and a coarser transmission grid and hence less expensive devices. A heuristic algorithm is then used to minimize the number of deployed channels in the configurations with slot blockers (OSSv2 and OSSv3).

In Fig. 3 we show the maximum network load (the sum of all network demands; the load is normalized by the channel data rate) that is supported in a 10-node network, for each architecture, under a random uniform traffic demand, when the number of transponders and the number of wavelengths are fixed. OSSv1 requires one channel per node to carry traffic while OSSv2 and OSSv3 start carrying traffic when only a single wavelength is deployed. As more wavelengths are deployed, OSSv2 and OSSv3 carry up to twice as much traffic as OSSv1 for the same number of transponders and wavelengths.

RING SIZE

Although an OSS ring could be dimensioned for an arbitrary number of nodes, physical impairments sustained by signals crossing the nodes limit the cascadability of the OSS nodes. Unlike OSSv1 nodes, which use components that are similar to those found in circuit switched networks (splitters, WSS, EDFA) and hence are subject to the same cascadability limitations, OSSv2 and OSSv3 nodes include not only optical filters but also optical gates, which may distort signals. Optical gates such as (reflective) semiconductor optical amplifiers ((R)SOA) add optical noise and non-linear distortions. The largest count (typically several dozens) of cascadable devices is obtained at the optimal trade-off between these impairments.

QOS SUPPORT

A modern metro ring network should be able to carry traffic with different classes of service (CoS), possibly under strict latency constraints, for instance to meet the Carrier Ethernet quality of service (QoS) specifications. In OSS, QoS support is achieved when client frames are encapsulated into slots, and when slots are inserted on the medium. In particular, CoS differentiation can be performed either during slot encapsulation (mixing frames with different classes in the same slot, but start filling slot with high priority frames) or at insertion time (prioritize adding slots containing more frames with higher CoS). Slot insertion on the fiber medium may be done according to a pre-defined schedule that is computed by a centralized controller, or according to reservations that are dynamically computed by each node in a distributed fashion, or simply opportunistically, i.e. by inserting data on the first available slot. Resource utilization of up to 80% with those methods was reported [10]. All methods are applicable to any of the OSS flavors. Observe, however, that OSSv3 is more flexible than OSSv1 and OSSv2 because all nodes can use any wavelength to send slots to any other node. Such flexibility facilitates decreased latency compared with OSSv1 and OSSv2.

PROTECTION

Protection in ring networks is typically achieved by using two counter-directional rings, with a wrapping or folding mechanism to isolate faults such as link or node failures. Such protection is applicable to OSS rings, which are compatible with both dedicated (resources reserved for both working and backup traffic) or shared (the same backup resources are shared to protect several working traffic streams) protection, or a combination of those to decrease network cost [11].

KEY DEVICES FOR AN OPTICAL SLOT SWITCHING NODE

SLOT BLOCKER

We show a slot blocker structure in Fig. 4a, consisting of a wavelength demultiplexer, one optical gate per wavelength that enables it to selectively erase any slot, and a wavelength multiplexer. The optical gate is one of the most crucial elements of the OSSv2/OSSv3 node as it is responsible for the (optical) quality of the transiting slots (when the gate is passing) and the inserted slots (when a gate is blocking, any remaining signal on the blocked wavelength may degrade the quality of a slot inserted further on the ring). Since a slot blocker structure contains several optical gates, it is especially important to minimize the cost and footprint of the optical gates without sacrificing functionality. Unfortunately, the cost of the slot blocker when implemented with discrete components has remained high for a long time. Recently, in order to decrease its cost, we proposed an implementation of the slot blocker using low-cost devices such as reflective semiconductor optical amplifiers (RSOA) [12] which have been developed for access networks: the packet reflective optical switch (PROS) shown in Fig. 4b [13]. Furthermore, the PROS requires only one fiber connector and is hence less costly than an integrated version of the slot blocker depicted in Fig. 4a, which requires two fiber connectors. The key specifications for the optical gates are their switching time (within the guard interval duration) and their extinction ratio, i.e. their ability to fully erase an incoming optical signal.

Active devices (in the standard InP platform) are excellent optical gate candidates due to their fast switching time, high extinction ratio, and high optical gain (SOA, RSOA, and EAM-SOA).

Considering the Silicon on Insulator (SOI) platform, various silicon-photonics devices have been proposed as building blocks for fast slot blocker structures such as Mach-Zehnder modulators (MZMs), ring resonator structures, or variable optical attenuators (VOAs). However, high insertion losses need to be compensated by optical amplifiers, and limited extinction ratio has been demonstrated [13].

Finally, hybrid III-V on silicon devices have been proposed [14] and may provide the benefits of SOAs as well as high integration capability.

FAST TUNABLE LASER

In circuit transmission, the major recent breakthrough to increase capacity has been the introduction of the digital coherent receiver, in combination with polarization division multiplexing and high-order modulation formats.

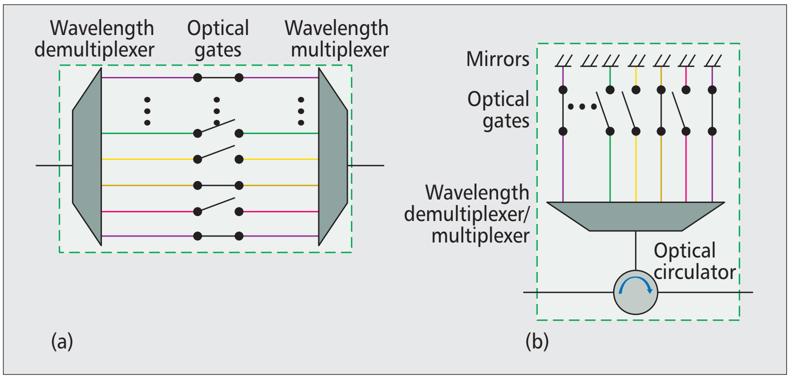

Figure 4. Slot blocker structures: (a) basic, (b) packet reflective optical switch "PROS".

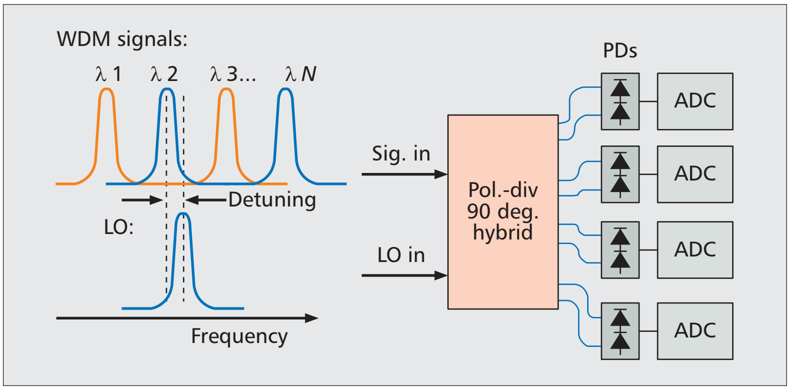

Figure 5. Comb of WDM signals and the local oscillator (LO) (left) at the inputs of the fast-tunable coherent receiver (right).

We use coherent detection in the OSS network to take advantage of the high spectral efficiency modulation formats such as polarization division multiplexing quadrature phase shift keying (PDM-QPSK) that is presently used in commercial 100 Gb/s transmission systems. Figure 5 shows a diagram of the WDM signals and local oscillator wavelength that are received with a dual-polarization 90 degree optical hybrid. Whereas traditional WDM systems use an optical filter to select only one of the wavelengths before the receiver, the coherent receiver is able to select one of the wavelengths from the comb without optical filtering. This selectivity is possible since neighboring channels will have a larger optical beat frequency between the channel and local oscillator that can be removed by the low-pass analog filtering of the photodiodes (PDs) and analog-to-digital converters (ADCs) as well as any filtering that may be done by digital signal processing. This "colorless" capability of the receiver allows any node to receive optical slots from any other node by rapidly tuning the wavelength of the local oscillator.

The tuning of the laser needs to be fast since data cannot be transmitted or received during this time. Therefore, we use devices that tune electronically, such as the digital supermode distributed Bragg reflector (DS-DBR) laser [15]. The DS-DBR is monolithically-integrated on

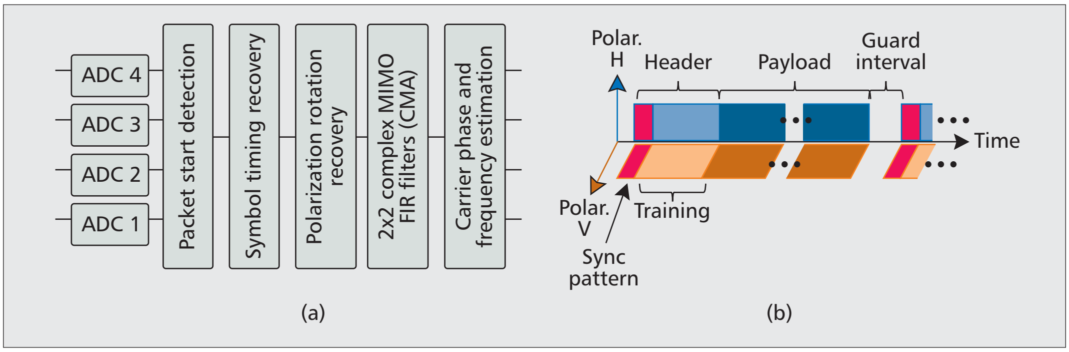

Figure 6. (a) Digital signal processing blocks required in a burst-mode coherent receiver; (b) structure of headers and payload for the packets.

The frequency offset between transmit laser and local oscillator, the polarization state of the received signal, and the timing of the data symbols can change on a slot-by-slot basis. All these parameters need to be recovered rapidly, i.e. much faster than the guard interval duration which is typically well below a microsecond.

InP with multiple sections that operate with current injection. The gain and SOA sections produce and amplify light, respectively, and the front, phase, and rear sections allow for tuning across the wavelength band.

The phase noise of the transmitter and local oscillator lasers will negatively impact the performance of the network, especially coming from the local oscillator laser at the coherent receiver in the presence of fiber dispersion. The DS-DBR linewidth has contributions from low frequency noise (at frequencies < ~100 MHz), mainly coming from 1/f tuning-current noise, white noise at intermediate frequency (at frequencies from ~100 MHz to several GHz), and a relaxation oscillation at high frequency (at a frequency of several GHz). For high symbol rate systems, the intermediate and high frequency noise will cause the most serious impairments since this noise is more difficult to track with digital signal processing.

When designing the electronic drive circuitry of the laser, care must be taken to not introduce excessive phase noise on the laser from electronic noise on the driving currents while maintaining fast wavelength tunability. Using the DS-DBR laser as the local oscillator, we have demonstrated rapid and accurate wavelength switching, with frequency offset <340 MHz after 80 ns, and a linewidth of 0.62 MHz after 120 ns [2]. To achieve these results, the phase section of the laser was used to compensate for frequency offsets and drifts caused by electronic carrier settling and thermal effects in the laser. With the phase compensation technique, rapid recovery of PDM-QPSK optical data with a bitrate of 112 Gb/s was achieved, even with up to 1280 km of fiber transmission.

BURST MODE RECEIVER

Coherent detection is now a commercial reality for circuit switching, but the use of a fast tunable laser as the local oscillator and burst-mode operation introduce a number of new challenges. The frequency offset between transmit laser and local oscillator, the polarization state of the received signal, and the timing of the data symbols can change on a slot-by-slot basis. All these parameters need to be recovered rapidly, i.e. much faster than the guard interval duration which is typically well below a microsecond.

We designed and implemented a (non real-time) fast slot receiver relying on the algorithmic blocks depicted in Fig. 6a and the slot format depicted in Fig. 6b [16]. Independently of the modulation format, two PDM-QPSK headers are inserted at the slot beginning. The first 128 symbols are used to find the slot beginning, and 128 additional symbols that are used for channel estimation and initialize a 2 × 2 multiple-input multiple-output (MIMO) equalizer. We verified that, for slot lengths up to a few microseconds, the channel can be considered static over the payload, and therefore adaptive equalization is not required. After channel equalization, carrier frequency recovery is performed, and phase estimation is achieved with a maximum likelihood search. Finally, a decision is taken on the symbols, and the bit errors are counted on the payload. The algorithms are initialized on a slot-by-slot basis, and no specific block for chromatic dispersion compensation is used to cover the full range of distances discussed here. We showed in [16] that the receiver could decode slots independently modulated with various formats up to PDM-16QAM after transmission over 50 km of standard fiber *without amplification* in the context of datacenter, access, or small metro networks. Distances compatible with large metro or even core networks can be achieved with amplification.

CONCLUSION

We reviewed several optical slot switching ring networks for metro or datacenter applications, and their key building blocks: slot blockers for efficient wavelength utilization, and fast wavelength tunable lasers and burst-mode coherent receiver for high data rate transmission.

In order to ensure high system performance and data rate, it is essential that tunable lasers have sufficiently low phase noise. Suitable lasers are now commercially available, although the electronic control of these lasers must be enhanced to allow fast-switching capability. Burst-mode coherent reception is a novel challenge, and research breakthroughs were presented. We also described several technology platform options to implement a slot blocker. III-V material provides amplification and good optical performance and integration has been demonstrated at a research and commercial level, but the chip cost remains high. Silicon photonics also promises good optical performance, and integrated (but only passive) devices are currently commercially feasible. Hybrid III-V/silicon technology has the largest potential, combining the benefits of silicon and InP into integrated active devices. First building blocks have been demonstrated, but higher levels of integration are not yet commercially feasible.

Technology for optical slot switching nodes with discrete components is already available and lab prototypes exist. However, further integration, along with the development of other non-hardware based blocks such as a novel control plane, will be needed before high-data rate, coherent optical slot switching reaches commercialization.

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BIOGRAPHIES

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