then 300 fs and close to the jitter of the 80 Gb/s transmitter [8]. This indicates an excellent system performance of the high speed all-optical clock recovery based on the self-pulsating laser.

5. Summary

Optical clock recovery is a key function for signal processing in future high speed and flexible all-optical networks. Self-pulsating DFB lasers are developed for these applications. They are compact semiconductor devices, easy to operate, and tuneable in frequency via the driving dc currents. Their good performance as optical clock has been demonstrated in several system experiments. Important advantages are the ultra high speed potential exceeding that of electronics and the fast locking function, needed for operation in asynchronous packet switched networks.

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System Perspective for All-Optical Switching

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It is true that the past year has been one of significant changes in the telecommunications industry as a result of the recent market downturn. It is also true that before this, the telecommunications industry had experienced an explosive growth for a good number of years. For wired networks this growth was due to the unprecedented improvement in performance of the photonic technologies as well as proof of their maturity that has resulted in a spectacular decrease in transmission cost, which in turn has lead to the widespread adoption and construction of new fiber networks. At this point of the business cycle and in preparation for the next crest of the wave, it is appropriate to review research lines that have been maturing over the years and whose results may be incorporated in next generation products. The purpose of this article is to argue that all-optical logic and all-optical switching techniques are such research themes.

All-optical switching, signal processing and more generally optical computing has been the holy grail of researchers ever since the invention of the laser. General purpose all-optical processing is still a long way off and may never materialize as electronics possess and seem capable to maintain huge technical and cost advantages. However there are specialized applications in high data rate telecommunications, where low complexity all-optical processing circuits are ideally suitable to provide functionalities that electronic solutions cannot, so that they may be of commercial value.

In order for all-optical switching techniques to become a serious consideration, they must simultaneously possess four properties: (a) a considerable speed advantage and otherwise ability to simplify the circuit design, (b) switching energies that are similar to those of electronics (c) capability for integration and of course (d) an application domain where these advantages may be of use. It was relatively early recognized that for the implementation of all-optical gates, interferometric arrangements offered speed advantages and Boolean logic capability [1,2]. Figure 1 shows a generic interferometric arrangement drawn as a Mach-Zehnder interferometer, but which could in fact be any type of interferometer as the Sagnac or the Michelson.

The interferometer consists of two separate optical paths where the phase of the optical field may be independently controlled in a nonlinear optical medium by optical means. In the example of figure 1, assuming that on each of the two interferometer paths the phase of the optical field CLK may be changed by $\pi$ depending on whether or not one or both of the external controlling signals A and B are present, interference on the output coupler causes the result of the Boolean addition XOR between A and B to be written on signal CLK. The rest of the Boolean operations may be implemented similarly.

Earlier research efforts used optical fiber as the nonlinear material partly due to its ultrafast Kerr nonlinearity and mainly because it was so much more easily available than for example optical semiconductor devices. Very spectacular results in terms of speed have been achieved using the nonlinear optical fiber, Sagnac interferometer, including the demultiplexing of a 10 Gbps channel from a 640 Gbps data stream in a 1.28 Tbps transmission experiment [3]. Unfortunately the Kerr nonlinearity of optical fiber is weak, requiring the use of long pieces of fiber, making the devices hard to integrate and their switching energies high. In the example given above the interferometer used 450 m of fiber and required about 2 pJ of switching energy for 1 ps pulses [4], so that operation of the switch...
at the full data rate becomes energy-wise expensive.

It was the realization that fast phase variations can also be obtained in semiconductor optical amplifiers (SOAs) as a result of the relation between the refractive index and the carrier density, that has more recently lead to a whole new class of compact and very low switching energy devices. These can be broadly separated to either discrete SOA interferometric gates or integrated devices. The discrete devices are single optical path designs that are either of the dual arm Sagnac type [5-7], or single arm type [8,9] and include a single SOA. Integrated devices have been demonstrated by both monolithic integration or hybrid integration of SOAs on Si-based planar lightwave circuits and follow the Michelson or the Mach-Zehnder designs. The technology status of semiconductor optical gates including integration activities have been very thoroughly reviewed in reference [10]. The basic nonlinearity that these devices exploit is resonant and for this reason switching has been shown repeatedly to be possible with energies of few fJ for pulses of few ps duration [11-13], in very compact devices. In this context demultiplexing from 336 Gbps to 10.5 Gbps and wavelength conversion experiments have been shown [14], as well as more taxing experiments for the switching element at the full data rate of 100 Gbps [15].

From the previous discussion it must be obvious that the recent advances of all-optical switching techniques have addressed the issues of speed, switching energy and capability for integration. It remains to clearly identify application regimes for these devices where they display superior suitability compared to alternative solutions. Applications related to ultra-high data rate single channel TDM transmission such as demultiplexing were identified early. All-optical regeneration was also identified as a key functionality that can be provided by optical gates, by taking advantage of their amplitude and timing jitter suppression properties [16-18]. It was however the overwhelming penetration of WDM systems and the need for fast wavelength converters that has provided one of the main application areas [12, 19-20], because of the very steep transfer function and high extinction ratio that semiconductor interferometric devices can give.

Looking further ahead and in view of achieving better resource use at the network level, some form of packet or burst switching is likely to be needed. Currently only circuit optical switches are available in the market. All-optical packet switches exist only in laboratories and the demonstrations available do not offer the distinguishing features of packet switching, that is, on-demand use of bandwidth and the ability to switch busy traffic without excessive packet loss. Proposals of how to build ‘true’, optical packet switches have been made in the past [21] and these rely on algorithms that guarantee lossless routing through the switch and optimal cost scaling of the switch in terms of the burstiness of the data. Such a switch consists of three main units: (a) the electronic control unit that is responsible for running the routing algorithm from information obtained from the packet headers, (b) a packet slot interchanger unit at the input of the switch that plays the role of buffer to avoid internal collisions and (c) a space switch for output routing. The routing algorithm is still performed in the electronic domain, but the control of the optical switching elements can be done all-optically, so as to avoid the complex electronic driver circuits for the optical switches and to improve the overall switch speed. To implement such design based on the all-optical control of the switching elements, several functionalities are needed including packet synchronization [22] and parity checking [23]. Key optical circuits are also needed as, for example, 2x2 exchange bypass switches [13] for the packet slot interchanger or clock recovery units that may operate on a packet basis. Figure 2 shows a recently demonstrated all-optical circuit to acquire clock from packets [24]. The packet clock recovery unit uses a Fabry-Perot (FP) filter with a free spectral range equal to the data rate followed by a nonlinear, high speed, optical gate. The role of the FP filter is to partially fill the ‘0s’ of the incoming packet and the optical gate employs its nonlinear transfer function to equalize the amplitudes of the partially filled ‘1s’.

Important features of this circuit are that it acquires clock within very few bits, the clock signal persists approximately for the duration of the packet, it does not contain any high speed electronics and does not require any external synchronization, so that it could be suitable to power an all-optically controlled packet switch.

In summary all-optical switching techniques have matured technologically, very significantly over the past few years and across all fronts. Advances have spanned from the material and device level, to the system and application level as well as performance and practicality. Improvements were the result of effort in a number of laboratories across the world and these have brought all-optical switching technology to the point of commercial exploitation. The next few years will call the commercial verdict on these efforts.

References
We review the physical processes that are responsible for ultrafast gain and index dynamics in semiconductor optical amplifiers and which impact high-speed optical switching applications.

All-optical signal processing is expected to play an important role in future high-capacity optical communication systems. Primary incentives for this evolution are the larger data rates that can be handled by all-optical devices, as well as the cost-reduction and increased flexibility that may be achieved by avoiding conversions between the optical and the electronic domain. In order to be practical and competitive, all-optical switching devices should fulfill criteria similar to those of electronics, i.e., be small and allow integration of different functionalities, and have the potential for cheap mass-production. Presently, semiconductor optical amplifier (SOA) based devices are among the primary contenders for integrated all-optical devices. The large gain and large differential gain of SOAs allow switching with power levels in the range of milliwatts, and various functionalities have been demonstrated in a number of different schemes at speeds in excess of 100 Gb/s, e.g. wavelength conversion at 168 Gb/s [1]. In this paper we will review and discuss the physical processes that impact the operation of SOAs at such high data-rates.

Common to the various schemes utilizing SOAs as the main switching element is the exploitation of saturation effects in the active region of the waveguide. When an optical beam is injected in the amplifier, the gain of the amplifier is saturated and, in consequence of the induced change of the carrier density in the active region, the refractive index of the waveguide is changed, cf. the qualitative illustration in Fig. 1. Both effects can be utilized for all-optical switching of a data signal [2]. In the simplest scheme of cross-gain modulation (XGM), the gain change simply controls the amplitude of another (probe) beam transmitted through the wave-