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Semiconductor Optical Amplifier-Based All-Optical Gates for High-Speed Optical Processing

Kristian E. Stubkjaer

Invited Paper

Abstract—Semiconductor optical amplifiers are useful building blocks for all-optical gates as wavelength converters and OTDM demultiplexers. This paper reviews the progress from simple gates using cross-gain modulation and four-wave mixing to the integrated interferometric gates using cross-phase modulation. These gates are very efficient for high-speed signal processing and will open up interesting new areas, such as all-optical regeneration and high-speed all-optical logic functions.

Index Terms—Add/drop multiplexer, optical gate, optical processing, semiconductor optical amplifier, wavelength converter.

I. INTRODUCTION

FOR YEARS, there has been a desire to realize all-optical computers using digital optical elements. Clearly, this is very ambitious since optical elements lack the packing density of electronic gates because of the much shorter interaction length of electrons compared to photons. Nevertheless, it is very realistic to aim at simple optical-signal processing in telecommunication networks. The requirements are not for massive processing, but rather the possibility of simple optical processing at bit rates close to or beyond the bandwidth of presently available electronics, i.e., 40 Gb/s and above. The all-optical processing is especially attractive in the high-capacity core networks where we want to avoid opto-electronic conversion. The all-optical functions needed in add–drop and cross-connect fabric are wavelength conversion, add–drop-multiplexing (wavelength and time), clock recovery, regeneration, and simple bit-pattern recognition.

For most of these functions, we need simple gates that can be controlled optically, as shown in Fig. 1. A gate used to modulate a CW signal or a pulse train can function as a wavelength converter, or part of an optical regenerator, respectively, whereas gating of an optical input signal can be used for time demultiplexing, e.g. Moreover, optical elements that can perform simple logic operations such as AND or XOR will be useful for routing functions for example.

All optical gates are realized by optical nonlinearities in both glass and semiconductor material and are relying on mechanisms, such as four-wave mixing, cross gain, cross-phase and cross-absorption modulation, or combinations of these.
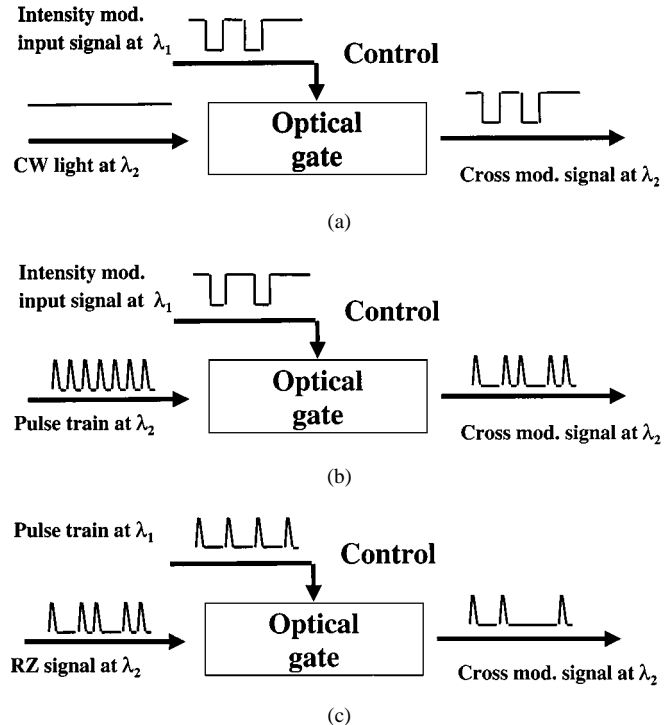
Fig. 1. Schematic of optically controlled gate used for: (a) Wavelength conversion by gating of CW light. (b) Regeneration and wavelength conversion by gating of clock pulses. (c) Demultiplexing–sampling by gating of optical signal using clock pulses.

Depending on the transfer function of these gates, inverted or in-phase output signals result (see Fig. 2). Clearly, we need modules that

1) operate at low optical power levels;
2) are easily adjustable to the system bit rate and to the transmission protocol;
3) are polarization independent; and
4) can be cascaded in several stages.

This paper is primarily devoted to nonlinear elements based on semiconductor optical amplifiers (SOAs). The history of SOAs is going back to the beginning of the 1980s, where the development effort was clearly motivated by the need for linear amplification in point-to-point systems. Challenges included the realization of low-facet reflectivities and high fiber-to-fiber gains by also reducing the coupling losses (see for example [1] and [2]). With the arrival of the erbium doped

Fig. 2. Schematic of optically controlled gate and the dependency of the output signal on the transfer characteristic of the gate.
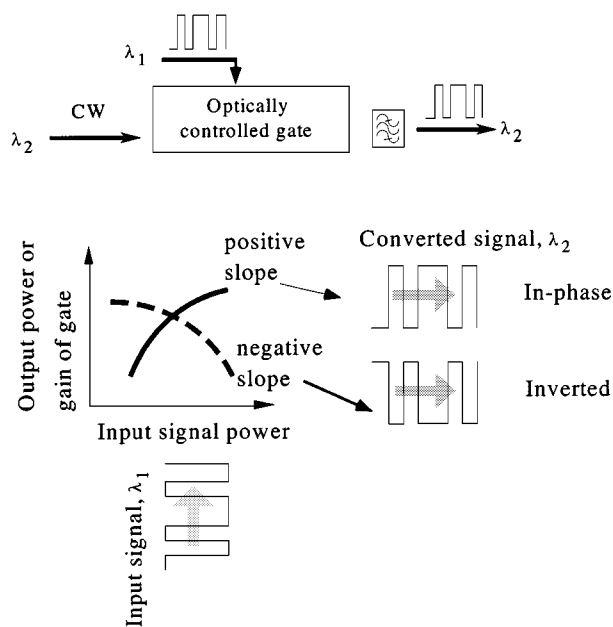
fiber amplifier (EDFA) around 1990, the SOAs were, however, almost out-competed as linear amplifiers. The EDFAs featured lower noise levels and also much better crosstalk properties for multichannel amplification, due to the much longer recombination times for the excited states in Er compared to the very fast carrier dynamics in semiconductor material. SOAs still have a potential price advantage over EDFAs since they are powered directly, so they may be useful as amplifiers in access networks. Moreover, they can provide solutions outside the 1500-nm band where fiber-based amplifiers are more difficult to realize.

II. XGM GATE

The nonlinear behavior that is a drawback for the SOA as a linear amplifier makes it a good choice for an optically controlled optical gate. First reports of optically controlled SOA-gates were made in [3] and [4]. In both cases, cross-gain modulation (XGM) was explored: The input signal is used to saturate the gain and thereby modulate a CW signal (probe) at the desired output wavelength.

The wavelength conversion application has been a very strong driving force behind the investigations of XGM-gates. By the middle of the 1990s, it was very clear that wavelength division multiplexing (WDM) is a very competitive way to upgrade for higher transmission capacity. Moreover, it became obvious that WDM networks with all optical cross connects will be needed for efficient transport of information, e.g., [5]–[7]. Wavelength conversion–translation within the network or at its interfaces is needed for efficient dynamic transport reconfiguration, high-level restoration, and utilization of the fiber bandwidth [8], [9]. The converters make it possible to assign wavelengths on a link-by-link or a subnetwork basis, thereby relaxing the requirements to the wavelength precision throughout the whole network [8]. Moreover, wavelength

conversion eases the recovery from link or node failures by allowing for local rather than global reconfigurations in the network, e.g., [8]–[14]. Thus, there are very good arguments for pursuing efficient wavelength conversion.

The cross-gain modulated (XGM) gate is extremely simple to assemble. It is polarization insensitive because of polarization-independent SOA gain, and it is very power efficient. It also turned out that the gate can be extremely fast, and, by 1998, bit rate capabilities of 100 Gb/s were reported [15], [16]. At first glance, it seems impossible to reach this speed due to the relatively slow carrier dynamics with lifetimes in the order of 100 psec [17]. Detailed analyzes can, however, explain the significant role of gain saturation in achieving high speed [18]. The prospects of achieving even higher bit rates look fine with the use of quantum dot material. Pump-probe experiments reveal very fast gain dynamics [19] in amplifiers made from this material.

The XGM gate has a number of shortcomings, such as inversion of the input–control signal and the relatively large chirp of the output signal due to the large gain modulation. Nevertheless, the gate has been used with fine results in a number of switch block experiments, e.g., [20], [21]. Moreover, the gate has been used to pioneer very interesting work on format conversion from RZ to NRZ and vice versa [22]. OTDM to WDM transmultiplexing can also be achieved [23], [24]. The gate has also been used for demonstration of header erasure and replacement in various optical packet switching schemes [25], [26]. It remains an interesting challenge to come up with new combinations of such gates to achieve new functionalities.

SOA gates exhibiting optical bistability have also been realized using SOAs or laser diodes with higher facet reflectivities, e.g., [27], [28]. The bistability is a result of the interaction between the gain and index variations in the resulting cavity. These bistable elements do, however, have limited bit-rate capabilities in the order of 1–5 Gb/s, making them unattractive compared opto-electronic alternatives.

III. XPM GATES

Gates with better performance are achieved by placing SOAs in interferometric configurations, such as those shown in Fig. 3. In these gates, the optical input signal controls the phase difference between the interferometer arms through the relation between the carrier density and the refractive index in the SOAs (cross-phase modulation, XPM); thereby a CW light or a pulse train can be gated [29] or control pulses can be used to gate the input signal.

For stable operation, the XPM converters must be integrated. The first monolithic structures reported [30] were based on Michelson interferometers [Fig. 3(b)], realized by cutting sections out of the 4 × 4 space switch with SOAs made by Ericsson Components [31]. An early realization of a two-port Mach–Zehnder structure was based on a back-to-back coupling of the Y-lasers made by Alcatel SEL [32]. Following these early versions of XPM gates, an impressive activity on monolithic integration of interferometric gates has taken place [33]–[39], making these gates one of the test grounds for monolithic integration of active optical elements.
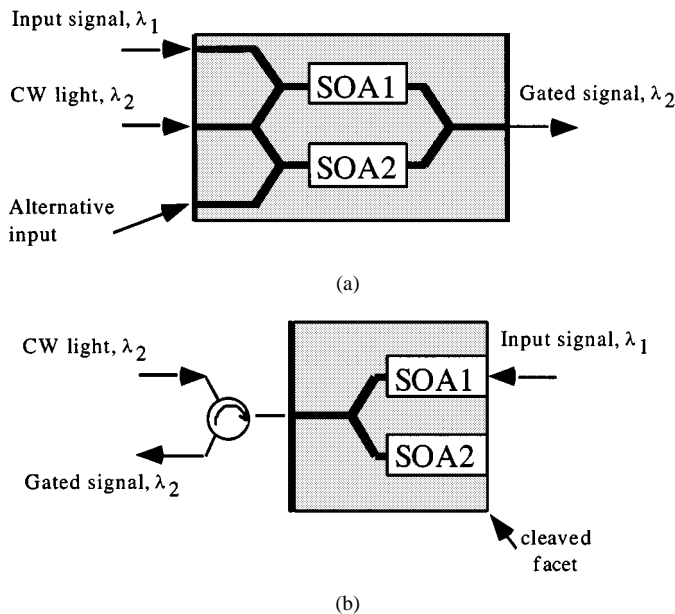
Fig. 3. Optical gates using MZI and MI structures with SOAs in the interferometer arms.

Fig. 4. Schematic for differential operation of Mazh–Zehnder gate to create short-switching windows.

As mentioned, the Mach–Zehnder structures started with two-port devices, but now they have been developed into structures with separate waveguides for coupling the input signal into only one of the interferometer arms, as shown in Fig. 3(a). The idea is that the input signal depletes the carrier concentration in only one of the SOAs, thereby creating the wanted phase difference between the two interferometer arms in a very efficient way [34]–[37].

The Mach–Zehnder gate has even been refined using bimodal waveguide structures [39]. They allow the input signal and the probe signal to co-propagate in the structure using different spatial modes. Structures including integrated CW light sources and structures with integrated optical preamplifiers are also reported [40], [41].

Michelson interferometric gates have simpler structure since they offer direct access for the input signal to the SOAs [30], cf. Fig. 3(b). The MI converter has a reflective facet, making it a folded version of the MZI converter. Nonlinear loop mirror configurations with SOAs like the SLALOM (semiconductor laser amplifier loop mirror) and the TOAD (terahertz optical asymmetrical demultiplexer) are also reported [38], [42]–[44]. Such gates have the advantage of being inherently balanced, but only RZ signals can be handled. Another interferometric scheme that has been used in experiments is the UNI that requires only a single SOA [60].

Hybrid integration of SOAs on Si-PLCs has been reported as an alternative to the monolithic integration of the interferometric gates [45]. The approach is interesting since waveguide technology in Si is relatively mature.

The interferometric converters have the advantage of very steep transfer functions enabling extinction-ratio regeneration of the gated signals. Only small input-signal levels are needed to introduce a π phase difference between the interferometer arms, so that a very efficient conversion is obtained almost independently of wavelength. Because of the small modulation associ-
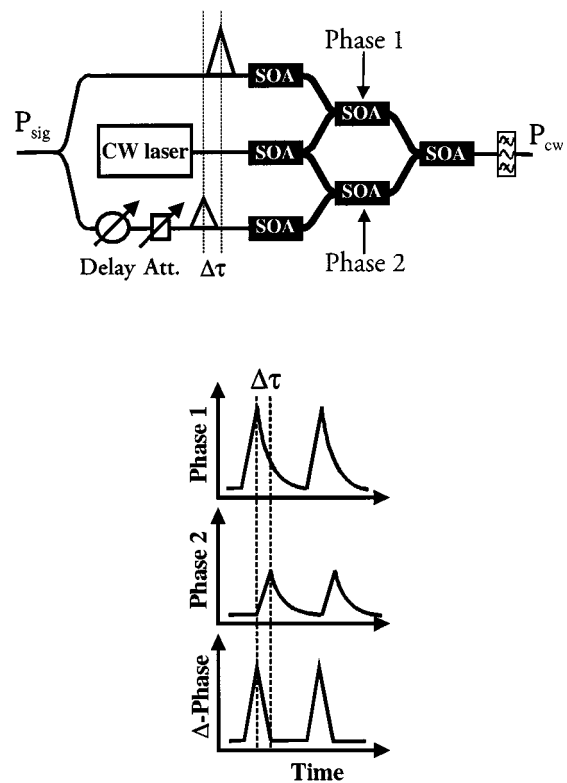
ated with the π phase shift, the frequency chirp of the output signal will also be small compared to, e.g., the XGM converter [30], [46], [47].

Besides signal waveform and spectral reshaping, the interferometric gates have high optical SNR ratios for the output signals. Moreover, the noise is redistributed due to the transfer function [48], [49]. As a result, the noise is accumulating less rapidly than for a chain of optical amplifiers. This allows for cascading of several gates [50]. The regenerative properties of the interferometric gates are important for construction of all-optical cross connects, in which other components-like amplifiers may degrade the signal quality.

Like the XGM gates, the interferometric XPM gates have achieved high-speed operation. Thus, wavelength conversion at 100 Gb/s was recently achieved in a Mach–Zehnder structure [51].

Even faster operation can be achieved with the interferometric structures by controlling both arms of the interferometer in a differential way, as shown in Fig. 4, thereby creating very short switching windows (e.g., [52] and [53]) as is demonstrated experimentally in Fig. 5 [54]. It is clearly seen that the trailing edges become steep when the differential scheme is applied. Gates operated in the differential configuration have successfully been used for time demultiplexing from 160 to 10 Gb/s. Moreover, very elegant add–drop into an OTDM bit stream can be achieved with a Mach–Zehnder interferometer [55]. An extension of the add–drop experiment to 80 Gb/s (also using the Mach–Zehnder from ETH) is shown in Fig. 6 [56]. Recently, the differential-control scheme has also been used to demonstrate wavelength conversion at an impressive bit rate of
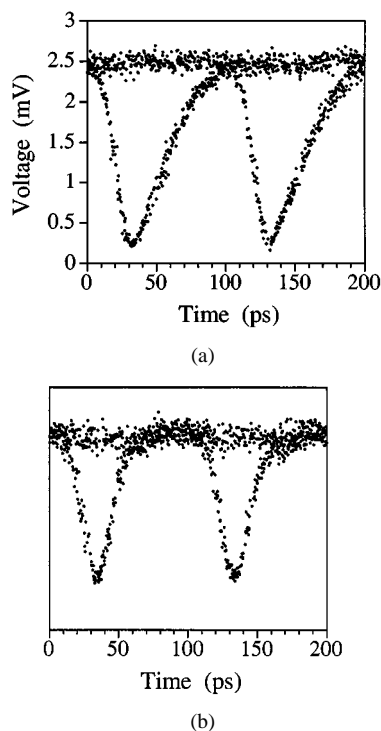
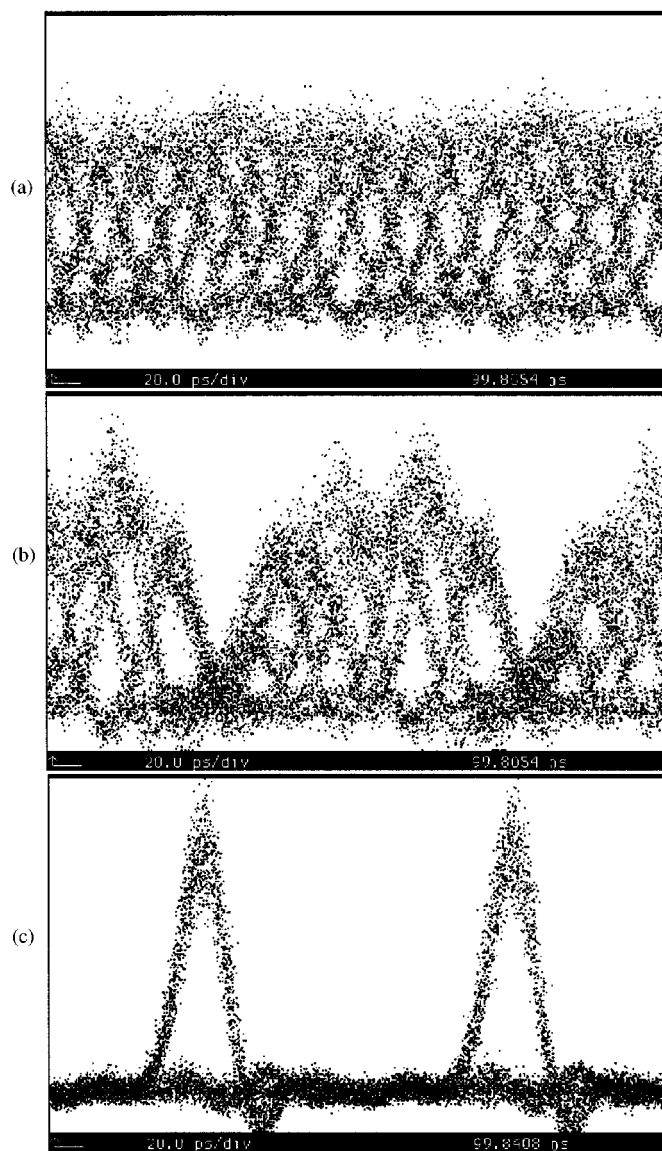Fig. 5. Examples of gated output waveforms (a) without and (b) with differential control applied [54].

Fig. 6. Add-and-drop functionality at 80 Gb/s using an SOA based Mach–Zehnder interferometer. Top trace is the 80 Gb/s input signal (a), whereas the two lower traces show the 7×10 Gb/s signal with a vacated timeslot (b), and the dropped 10 Gb/s signal (c) [56].

168 Gb/s [57]. High-speed operation has also been achieved, using nonlinear loop mirrors with SOAs demonstrating demultiplexing from 250 Gb/s [58]. For demultiplexing of OTDM signals, the semiconductor-based interferometers do not yet achieve the speed of fiber-based NOLMs (e.g., [59]), but they have the advantage of being very compact and therefore potentially simpler to use in real systems.

The first packaged MZI structures have already been realized and tested in field trials. It should be noted that the gates still need refinement and as does the schemes for control of their operating point, but it is interesting to see how fast the development of these advanced optical gates has been since the start around 1993. The interferometric SOA gates have turned out to be important building blocks for development of all-optical regenerators and simple signal-processing elements as described below.

IV. FOUR-WAVE MIXING IN SOAs

Instead of the cross-gain and cross-phase modulation in SOAs, it is also possible to utilize four-wave mixing (FWM). In fact, impressive work on wavelength conversion with FWM in SOAs was published already in 1989 [61] and numerous results have been published since then. The FWM scheme (see Fig. 7) is inherently fast and the gates have the advantage that many WDM channels can be handled simultaneously [62].

The input-to-output signal efficiency of the gate decreases with the wavelength separation of the pump and the input signal, but experiments using SOA gates with very long cavities have resulted in conversion efficiencies approaching 0 dB [63], which is important for good optical SNR at the output.

Clearly, the output signal wavelength depends on both the pump (λ_p) and the input signal (λ_i) wavelengths, so the pump

must be tunable even for converters with fixed output wavelength. Moreover, two pumps will be needed to ensure polarization-insensitive operation since the FWM process is polarization sensitive [62], [64]. Because of the relatively complex pumping scheme, FWM gates will probably only be used at bit rates above 100 Gb/s. Wavelength conversion at 100 Gb/s has been achieved for conversion over 3.2-nm wavelength [65] and impressive results have also been achieved for conversion over larger wavelength spans. Examples are 40 Gb/s over 24.6 nm [66], and 2.5 Gb/s over 80 nm [67].

Also, time-demultiplexing from 100 to 10 Gb/s is reported with FWM gates [68], and the gates have been used for clock extraction of a 6.3-GHz clock from a 400-Gb/s signal [69]. Another potentially important application is dispersion compensation by midspan spectral inversion where the optical phase conjugation of the FWM process is useful [70]. It should be noted that very impressive results on midspan spectral inversion have
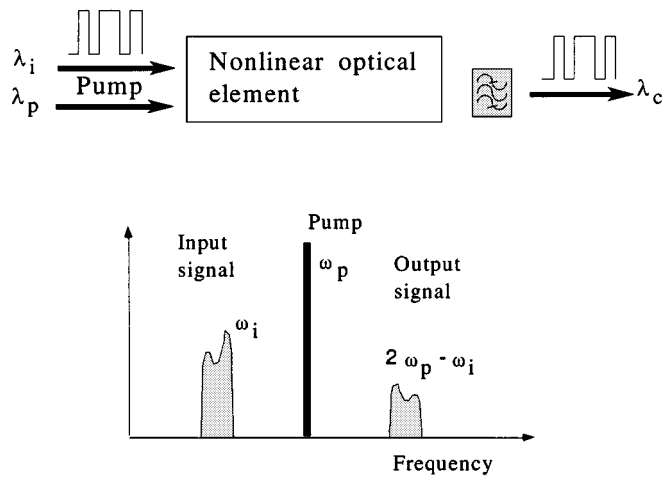
Fig. 7. Schematic of four-wave mixing gate.

Fig. 8. Scheme for improved optical regeneration using the Mach–Zehnder interferometer as an inverting AND gate [76].

(a)

(b)

Port number		
#1 (IN1)	#2 (IN2)	#3 (XOR)
0	0	0
0	1	1
1	0	1
1	1	0

(c)

Fig. 9. Schematic of Michelson interferometer used as an XOR gate, including the detailed operation principle (b) and the XOR truth table (c) [89].

also been reported using optical fiber as the nonlinear element [71].

V. ALL-OPTICAL 3-R REGENERATORS

As the all-optical networks emerge, regenerators become key elements since signals experience different transmission paths in the network. Clearly, full 3-R regeneration is most attractive, but 2-R regeneration offering re-amplification and reshaping may also be useful. The interferometric (XPM) gates described above are well-suited for optical regeneration since they offer 2-R regenerating capabilities due to their nonlinear transfer function. Experiments with cascaded links have shown how these gates can redistribute noise caused by optical amplifiers and other network elements, and thereby ensure slower noise accumulation [72].

As shown schematically in Fig. 1(b), full regeneration can be achieved by using the input signal to gate extracted optical-clock pulses [73]–[75] and, in some cases, even better performance may be achieved with more refined use of both input arms of the interferometers, as illustrated in Fig. 8 [76]. The optical clock can be extracted optically for example with mode-locked or self-pulsating lasers [77], but combinations with electronic clock-recovery units is clearly also a solution to be considered [78]. As described above, the SOA-based gates can achieve data rates exceeding 100 Gb/s, so it should be possible to realize very fast optical regenerator units.

Fine examples of two-stage optical regenerators are also published. In one of the first reports [79], an XGM gate is used in the first stage to sample the input signal with extracted clock pulses and to equalize input power fluctuations. In the second stage, a Mach–Zehnder interferometric gate is used to regenerate the extinction ratio, resulting in complete regeneration. The scheme has been demonstrated for cascading a number of 140-km links in a 10 Gb/s loop experiment, thereby allowing for transmission over more than 200 000 km of fiber [80]. It should be noted that the regeneration is associated with wavelength conversion, so the regeneration can be combined with wavelength switching functionality. A two-stage regenerator arrangement can also be used for simultaneous synchronization of bit streams as described in [81].
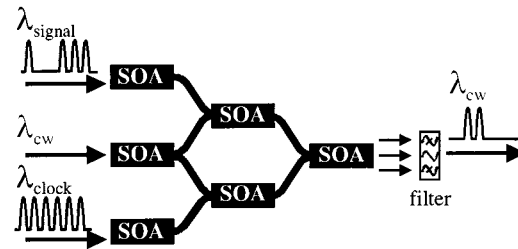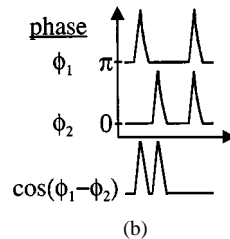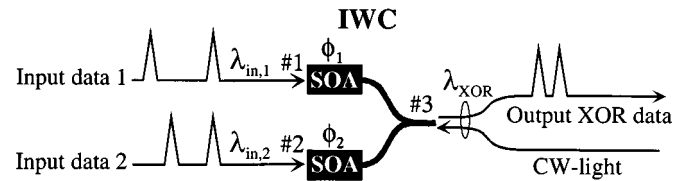
VI. ALL-OPTICAL LOGICAL GATES

As the switch nodes in optical networks get more optical functions on board, it becomes desirable also to be able to do simple all-optical logic operations. Early experiments with all-optical logics were based on fiber nonlinear-loop mirrors, e.g., [82], [83], but similar functionality can be achieved with interferometric gates using SOAs as the nonlinear element [84], [85].

The XOR gate is of special interest since it is the basic building block for a wide range of functions. Clearly, the gates should operate at high bit rate to be competitive to their electronic counterparts. High-speed XOR gates based on loop and UNI configurations are reported in [86] and [87], while integrated versions based on XPM gates are reported in [88] and [89]. The function of the XPM gate used as an XOR gate is shown schematically in Fig. 9 [89]. The data signals launched into the two SOAs causes a phase modulation (ϕ) of the CW-light propagating in the SOAs. At the output of the interferometer, the CW light from the two SOAs interferes either constructively or destructively, depending on the phase difference between the two arms. This
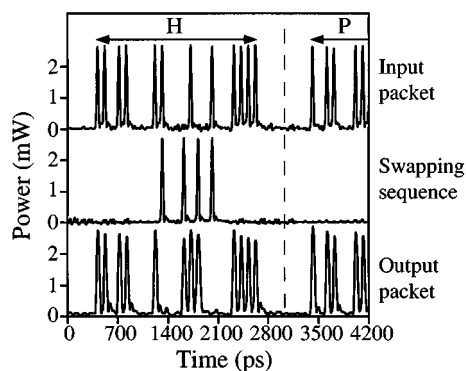
Fig. 10. Experimental demonstration of header replacement by XOR gate using a swapping sequence. Measured input and output packet sequences show header (H) and parts of the payload (P) [90].

leads to logical XOR of the two input data signals, as indicated by the truth table also shown in Fig. 9. Although the XOR gates are demonstrated at up to 20 Gb/s, they have the potential of much higher data rates as discussed above.

As an example of an application, Fig. 10 shows the experimental demonstration of an XOR gate used for optical label swapping at 10 Gb/s [90]. Using a simple swapping sequence, only the necessary changes in the header section are made, while the package as a whole undergoes wavelength conversion at the same time. It is seen how the use of the XOR gate eliminates the need for guard bands between header and payload, thereby bringing optical packet-switched networks one step closer to a practical implementation.

Reports on more complex functions based on XOR gates realized from TOADs [43] are found in reports by BT Laboratories. Examples of their work include binary counters and parity checkers [91], [92]. No doubt all-optical logic for optical networks is an exciting field of research where we can expect much innovation.

VII. CONCLUSION

SOAs have become useful building blocks for all-optical signal processing. From the early 1990s, the SOA-based structures have been developed into monolithically integrated interferometric optical gates that offer many advantages, such as signal reshaping and noise suppression. Experimentally, it is shown that these gates can operate as wavelength converters and OTDM demultiplexers at bit rates in excess of 100 Gb/s. It will be a continuing challenge to reach even higher bit rates by the use of, e.g., new materials such as quantum dot material.

It is also a challenge to build these gates into next generation all-optical 3R regenerators and to use them as logic gates that can perform simple operations in the switch nodes of the all-optical networks. Very fine work is now emerging in the literature, but there is a long way to go before we are close to the capability of electronic signal processing built into switch nodes today. Thus, we have much interesting research ahead to improve the optical technology. Moreover, we will need careful networks and systems studies to understand the role sharing between optical and electronic building blocks in the networks.

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