

All-optical signal processing based on semiconductor optical amplifiers

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Abstract In this paper, we review the recent progress in the optical signal processing based on the nonlinearity of semiconductor optical amplifiers (SOAs). The four important optical signal processing functional blocks in optical switching are presented, i.e., optical wavelength conversion, optical regeneration, optical logic, and optical format conversion. We present a brief overview of optical wavelength conversion, and focus on various schemes to suppress the slow gain recovery of the SOA and improve the operating speed of the SOA-based optical switches. Optical regeneration including re-amplification, re-shaping and re-timing is also presented. Optical clock recovery that is essential for optical regeneration is reviewed. We also report the recent advances in optical logic and optical format conversion, respectively. After reviewing the four important optical signal processing functional blocks, the review concludes with the future research directions and photonic integration.

Keywords optical switching, optical signal processing, semiconductor optical amplifier, photonic integration

1 Introduction

Optical networks have become an important part of the global telecommunication infrastructure, and the demand for bandwidth is increasing rapidly [1–3]. This demand is mainly driven by new services in the telecommunication network, such as high-speed internet, video-on-demand, videoconference, videophones, etc. It is estimated that the bandwidth will be increased up to 100 Tbit/s within five years and to 1 Pbit/s within ten years. Basically, optical networks provide two functions: transmission and switching. The present transmission technologies are sufficient to

meet the demand for bandwidth. The emergence of dense wavelength division multiplexing (WDM) technology, allows hundreds wavelengths to be simultaneously launched into one optical fiber, and the transmission speed per wavelength channel can be increased to more than 100 Gbit/s. A transmission rate of 69.1 Tbit/s over 240 km has been reached by employing 432 wavelength channels at a bit-rate of 171 Gbit/s per channel [4]. However, at the nodes of the optical networks, where the transmitted optical signal needs to be switched, the switching function is still carried out electronically. This process is referred to as optical-to-electronic-to-optical (OEO) conversion, which has turned out to be a significant bottleneck for the bandwidth of the networks. The bandwidth mismatch between the fiber transmission systems and the electronic switches is expected to become more complex in future switches that have to handle terabit/s data streams. Cisco (<http://www.cisco.com>) has presented the electronic router solution for the future 92 Tbit/s switching capacity. The whole routing system consists of 80 standard chassis, with 100 m² in volume, 60 t in weight and 1 MW in power consumption. It is estimated that the power consumption will reach 17.4 MW when the routing capacity is increased to 1 Pbit/s, this will require a medium size electricity power station to support the router.

Optical switching is envisioned as a promising solution to solve the above problems [5–7]. Compared to electronic counterpart, the utilization of all-optical signal processing in optical switching provides the advantages in terms of volume, power consumption, operating speed, cost, etc. The research results show that optical router can significantly reduce the volume, power consumption and weight with a factor of 1000 times [8]. In such an all-optical scenario, the optical signal processing needs to be carried out in integrated devices. Many research projects have been working on this area [9–13], one research breakthrough is that UC Santa Barbara has demonstrated the first 8×8 InP monolithic tunable optical router

(MOTOR) chip capable of 40 Gbit/s operation per port, serving as the packet-forwarding engine of an all-optical router with a switching capacity of 640 Gbit/s in the 4.25 mm×14.5 mm MOTOR chip [9].

Optical signal processing relies on the nonlinearity of optical materials, the materials would be III-V material, silicon or silica, polymer, and other materials. Using InP-based semiconductor optical amplifier (SOA) is promising because it provides large nonlinearity and allows large-scale photonic integration [14]. Currently several nonlinearities of SOAs have been used to perform the optical signal processing [14–16], such as cross-gain modulation (XGM), cross-phase modulation (XPM), cross-polarization modulation (XPolM), four-wave mixing (FWM), etc. To meet the requirements of the optical switching, optical signal processing has formed many functional blocks to construct the optical switching, such as optical wavelength conversion, optical regeneration, optical logic, optical format conversion, etc., as shown in Fig. 1.

In this paper, we review the progress in SOA-based optical signal processing. The paper is structured as follows. In Sect. 2, we present a brief overview of wavelength conversion, with a focus on various schemes to improve the operating speed of the SOA-based optical switches. Section 3 describes optical regeneration. Optical clock recovery is also included. Sections 4 and 5 present recent advances in optical logic and optical format conversion, respectively. We finally conclude in Sect. 6 with a brief discussion on the future research directions and photonic integration.

2 Optical wavelength conversion

All-optical wavelength converters based on nonlinearities in SOAs are considered as important building blocks for rapidly reconfigurable optical interconnects and fast switching in wavelength-division-multiplexed networks

[17,18]. Many SOA-based wavelength conversion techniques have been demonstrated [19], where XGM and XPM have been widely employed to realize wavelength conversion. These techniques are mainly related to the dynamic characteristics of carrier intensity in the SOA. In fact, the carrier recovery in the SOA is relatively slow, which is typically several tens to hundreds of picoseconds. The slow SOA recovery leads to unwanted pattern effects in the converted signal, and limits the maximum operation speed of the wavelength converters. To overcome the obstacle of slow SOA recovery, many approaches have been proposed to enhance the operation speed, including theoretical analysis and experiential demonstration [20–22], we review some typical schemes as following:

1) Differential scheme

The typical structure of the differential scheme is an SOA-Mach-Zehnder interferometer (MZI) with an SOA in each arm. The input pump signal is divided into two parts and launched into the SOAs with some differential delay. Based on this differential operation mode, the long live tail of the recovery can be suppressed. 40 Gbit/s operation speed is demonstrated in the MOTOR chip [9]. Some modifications have been proposed by using a differentially biased SOA-MZI switch operating in a bidirectional configuration [23]. Error-free 40 Gbit/s nonreturn-to-zero (NRZ) signal wavelength conversion is demonstrated with 1.7 dB negative power penalty, showing an enhanced reshaping regenerative capability. The SOA-MZI structure can be simplified, the MZI structure can be replaced by a delayed-interferometer (DI) configuration, where a single SOA is needed [24]. Phase modulated data format such as differential phase-shift-keying (DPSK) signal can also be wavelength converted by using SOA-MZI structure [25,26].

2) Detuned-optical filtering scheme

The core idea of this approach is to use detuned optical filter to extract the ultra-fast chirp dynamics in the SOA to cancel the slow recovery. The structure is composed of an

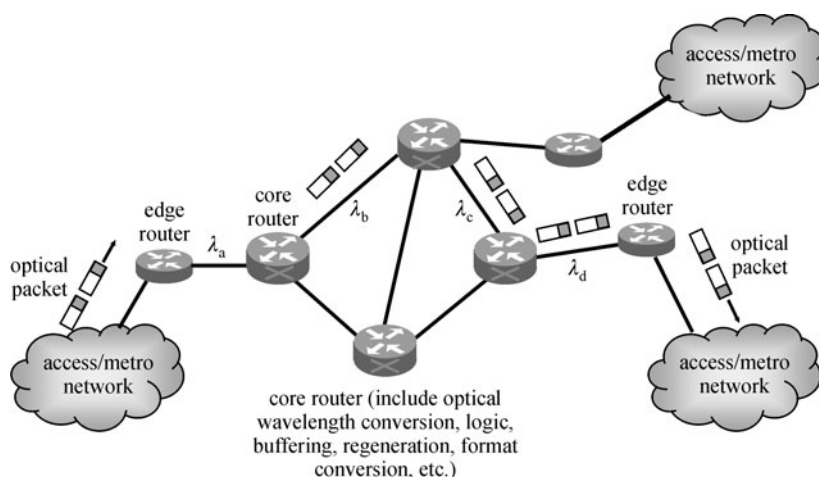


Fig. 1 Scenario of optical signal processing in optical networks

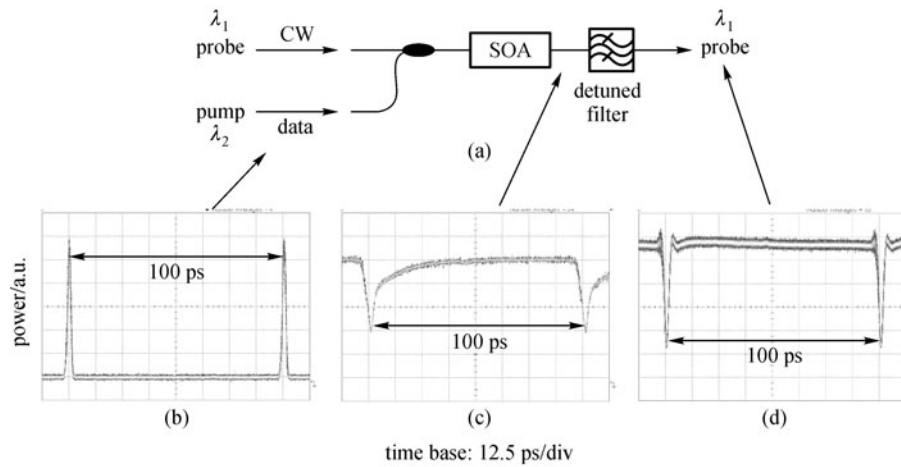


Fig. 2 (a) Detuned-optical filtering setup for speeding up SOA gain recovery; (b) input 10 Gbit/s pump pulses; (c) SOA gain recovery; (d) measured wavelength converter recovery with assistance of blue-detuned optical filter

SOA followed by detuned-optical filters, as shown in Fig. 2(a). Error-free 320 Gbit/s wavelength conversion has been demonstrated by employing an SOA with a gain that fully recovers in 56 ps [27]. The essential point in this approach is to employ optical filtering to select the blue-side band of the spectrum of the probe light, which leads to a full recovery time of less than 1.8 ps for the wavelength converter, as shown in Fig. 2(d). The operation principle is described in Ref. [28]. Detailed investigation for the configuration of the SOA followed by optical filters has been carried out in Refs. [29–32]. The optical filtering can be realized by using silicon-on-insulator (SOI) based DI, and 160 Gbit/s wavelength conversion using SOA and SOI-DI is demonstrated [33].

3) Turbo switch scheme

This scheme employs two cascaded SOAs as shown in Fig. 3. Error-free performance at 170.4 Gbit/s is demonstrated by using self-gain modulation in two cascaded SOAs [34,35], in which an optical filter between the two SOAs is used to block the pump and allows the modulated continuous wave (CW) beam to enter the second SOA. This configuration gives an enhanced high-speed response without compromising the optical signal-to-noise ratio (OSNR).

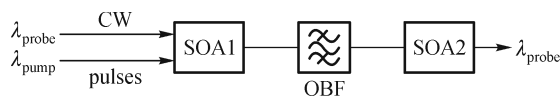


Fig. 3 Configuration of turbo switch

4) Holding beaming at transparency scheme

In this configuration, the gain recovery of SOAs is speeded up by injecting an optical CW light at the gain transparency point of the SOA [36]. By injecting 73 mW optical power near the transparency wavelength of the

SOA, a reduction in gain recovery time from over 200 ps down to below 40 ps is realized experimentally [37]. Wavelength conversion using XPM with an assistant light injection is investigated, showing the potential of fast gain recovery with a response time as low as 25 ps [38]. A scheme for wavelength conversion based on the combination of holding beam and blue-detuned optical filtering is proposed to potentially achieve 160 Gbit/s or even faster [39].

5) Ultra-long SOA (UL-SOA) scheme

UL-SOAs scheme is proposed because it can benefit from the semiconductor's fast nonlinear intra-band effects, such as carrier heating and spectral hole burning, while slow inter-band effects should be suppressed as far as possible. The first proof of concept for the high-speed potential was presented with an 80 GHz sine modulated signal [40]. This UL-SOA scheme has the capability to improve extinction ratio (ER). It is shown in Ref. [40] that a Bogatov-like effect caused by the fast intra-band effects in the UL-SOA saturated section is the reason for the ER improvement. The wavelength conversion with ER improvement in UL-SOAs is investigated numerically in Ref. [41], verifying the possibility of the high-speed potential with 100 Gbit/s operation.

6) Quantum-dot (QD) SOA scheme

QD SOA is very attractive because of the ultra-fast recovery time. It is shown in Ref. [42] that injecting more carriers to carrier reservoirs such as the excited state (ES) can significantly enhance XGM induced by spectral hole burning (SHB), and improves the high-speed XGM response at the ground state (GS) beyond 40 GHz. This is a large advantage of QD SOAs compared to quantum-well (QW) or bulk SOAs in the application of high-speed optical wavelength converters based on XGM.

A novel two-electrode QD-SOA has been proposed to enhance the gain recovery rate and XGM bandwidth [43],

as shown in Fig. 4. Compared with the common QD-SOA structure, the two-electrode QD-SOA can be adjusted flexibly to get nonuniform injection current density which makes carrier reservoirs like wetting layer (WL) or ES of QD sufficient along the entire cavity length of the SOA, thus SHB is enhanced to serve as the dominant gain saturation dynamics mechanism to accelerate the gain recovery, and the optical gain can be increased as well. The simulation results also show that distributing more current density in the second section of the two-electrode QD-SOA at large bias currents can greatly expand the XGM bandwidth.

Optical wavelength conversion using a QD-SOA and optical filtering is demonstrated at 80 Gbit/s [44]. Multicast wavelength conversion exploiting XGM in columnar quantum dot (CQD)-SOA is demonstrated at 80 Gbit/s at four 400 GHz spaced wavelengths [45]. Unlike the usual self-assembled Stranski-Krastanov grown QDs, which are inherently polarization dependent with only gain on the transverse electric (TE) mode, the used CQD-SOA has nearly isotropically shaped QDs, having transverse magnetic (TM) gain as well, enable the polarization-independence operation.

3 Optical regeneration

Optical regeneration can regenerate signal in the optical domain. In the optical networks, optical signal will attenuate and deform in propagation, stem from the combined effects of group velocity dispersion in the fiber and devices, polarization mode dispersion, nonlinearities,

noise accumulation, inter-channel interactions, etc. [46]. Optical regeneration is used to overcome the signal degradation and improve signal quality [46–49]. In general, the regeneration can be re-amplification and re-shaping (2R), and re-amplification, re-shaping and re-timing (3R). The regeneration system includes optical amplification unit, optical clock extraction unit and optical decision unit, as show in Fig. 5.

In present, erbium-doped fiber amplifier (EDFA), SOA and Raman amplifier have achieved optical signal amplification, so optical 3R regenerators focus on re-timing and re-shaping. The key technologies are optical clock recovery and optical switch with threshold decision function.

3.1 Optical clock recovery

1) Clock recovery based on mode-lock fiber loop laser (MLFL)

Typical scheme of clock recovery based on MLFL is shown in Fig. 6, where SOA acts as a nonlinear medium. The optical signal is injected into SOA, modulating the intra-cavity phase of fiber loop laser, forming mode-lock in the condition of cavity length matching, and thus achieving wavelength tunable clock pulses output. This scheme is demonstrated for recovering the clock frequency of the optical NRZ signal from 10–12.5 GHz repetition rate [50]. The intra-cavity dispersion-compensating fiber is used to eliminate chirp and asymmetry of SOA amplified pulses. The recovered clock consists of chirp-free Gaussian pulses at a diffraction limit with low timing jitter of 200 fs. The output clock pulses have 13 ps full width at half maximum

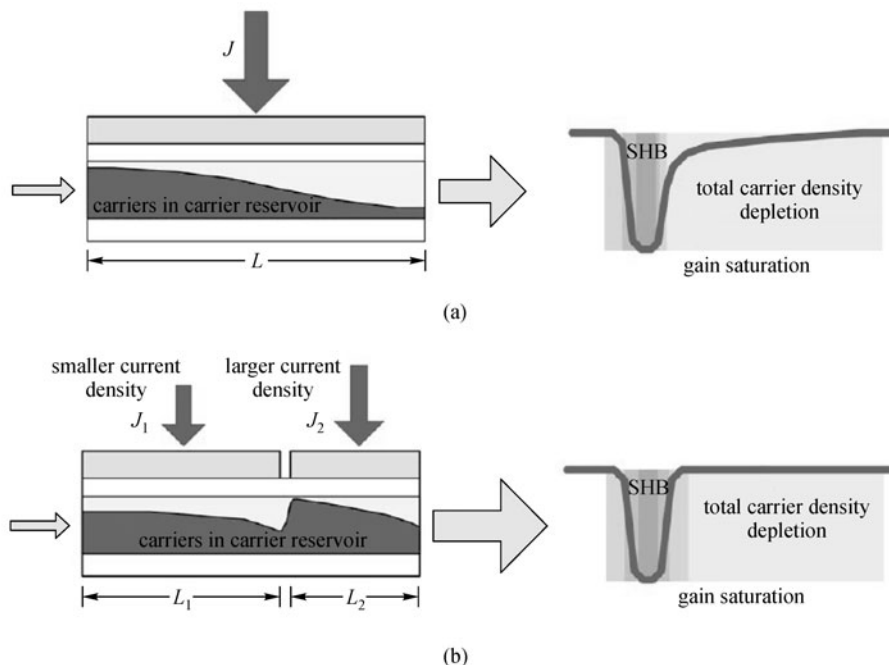


Fig. 4 Schematic view of QD-SOA. (a) Common QD-SOA; (b) two-electrode QD-SOA

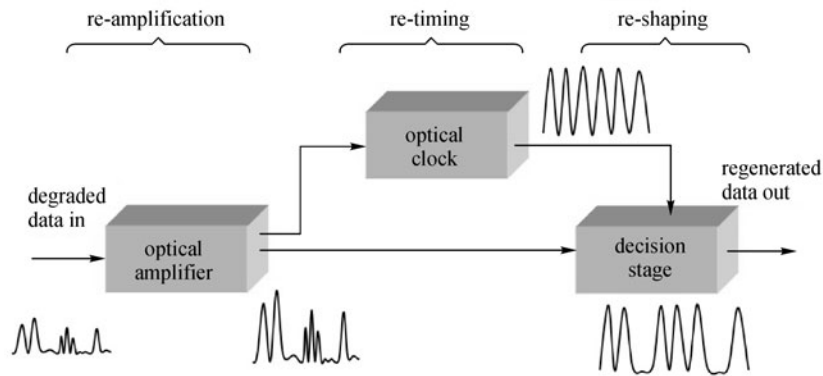


Fig. 5 Structure of all-optical 3R regenerator

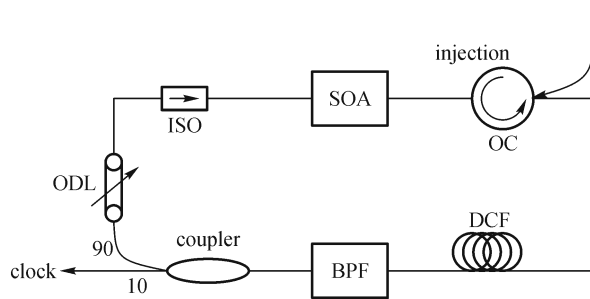


Fig. 6 Scheme of clock recovery based on MLFL

(FWHM) and 9 mW peak power. This configuration can easily recover the clock over a 40 nm tuning range that is determined by the SOA gain bandwidth.

MLFL has the advantages in terms of high repetition rate and flexible changing repetition rate. However, there are some major drawbacks. First, due to the long fiber loop cavity, clock is established and vanished over a long period of time when data packet clock is extracted, and the intra-cavity super-mode noise is difficult to be suppressed; second, the fiber-based structure is affected by environment easily and is difficult to be stabilized.

2) Clock recovery based on mode-lock semiconductor laser diode (MLLD)

MLLD-based clock recovery has a similar operating principle to the MLFL but with an integrated laser cavity [51–57]. Compared with the MLFL, the cavity of MLLD is much shorter and its fundamental frequency is pulse's frequency, so it does not generate super-mode noise. Furthermore, the operating rate of MLLD is very fast, can extract the optical clock signal with the time jitter less than 0.2 ps from 160 Gbit/s data signal [57]. A novel method of variable-in and variable-out optical clock recovery using a monolithic MLLD is presented in Ref. [53]. This method is based on regenerative active mode locking of the MLLD with an external seeding light, enable variable-in and variable-out optical clock recovery in case of variable wavelengths of input data light. 40 Gbit/s optical clock

recovery is demonstrated and stable clock recovery is achieved, with low timing jitter (< 0.3 ps) and low frequency chirping, even when the wavelengths of the input data and the output clock were widely changed by over 30 nm (1535 nm to > 1570 nm).

3) Clock recovery based on self-pulsating semiconductor laser

This scheme is based on the self-pulsating phenomenon. The laser is biased with DC current, operating in the free running and self-pulsating condition. The self-pulsating frequency can be synchronized by injecting external optical data signal, thus clock recovery is obtained. Using self-pulsating laser to achieve clock recovery has been presented in Refs. [58–61]. The characterization of the clock recovery properties of a self-pulsating, three-section distributed feedback (DFB) laser is presented in Ref. [59] by directly comparing simulation and experimental results for the dependence of the root-mean-square (RMS) timing jitter of the recovered clock signal on the characteristics of the input signal. The results show that the self-pulsating laser is effective for the degraded input signal by amplified spontaneous emission noise as it provides this level of jitter performance for input OSNR larger than 8.8 dB (0.1 nm noise bandwidth) [59]. Among the different types of the self-pulsating lasers, the amplified feedback laser (AFL) has a simple structure and easy tuning for injection locking. The beating frequency can be continuously changed over large frequency ranges with highly repeatable performance. 20 Gbit/s and 40 Gbit/s clock recovery is demonstrated using AFL structure in Refs. [60,61], the results show that AFL is a good candidate for optical clock recovery.

4) Clock recovery based on Fabry-Perot (F-P) cavity

Optical F-P has the properties of storing energy and releasing energy periodically, so it can be used to clock recovery [62–67]. The input optical pulse is injected into F-P filter, since the frequency interval corresponded to free spectral range of F-P filter is identical with the clock frequency of input optical pulse, and the central wavelength of input signal aims at the central of transmission

window, thus the discrete spectral with the information of clock can pass through the transmission window of filter, and the clock pulse outputs with certain amplitude fluctuation. Afterwards, a reshaping stage for clamping the output is used to achieve better clock pulse. The clock recovery scheme based on F-P filter has the advantages of simple structure and short clock establish time. The F-P filter is passive linear device, with the increase of F-P filter's fineness, the adjusting range of free spectral area is limited, so it is not suitable to handle wide-rang changed bit rate.

3.2 Optical regeneration

1) SOA-based interferometer structure

This structure uses the interferometric transfer function as a threshold decision gate to perform the regeneration function. The interferometric structure can be a Mach-Zehnder interferometer [68], or a Michelson interferometer [69], Sagnac interferometer [70] or nonlinear polarization switch [71]. Using the structure of SOA-MZIs and a 10 GHz F-P filter based clock recovery, optical 3R regeneration has achieved error-free 125000 km dispersion uncompensated return-to-zero (RZ) transmission over 1000 cascaded optical 3R regeneration stages [72]. The bit-error-rate (BER) performance evaluation using pseudo-random binary sequence (PRBS) $2^{23} - 1$ showed that after 12500 km uncompensated transmission, the power penalty at 10^{-9} BER is only 1.2 dB relative to the back-to-back case [72].

40-Gbit/s all-optical 3R regeneration is demonstrated based on semiconductor devices [73]. The setup is shown in Fig. 7. The 3R regenerator incorporates an amplified feedback laser (AFL) for all-clock recovery and SOA-DI as the optical decision gate. 40-GHz optical clock with low timing jitter and uniform amplitude is successfully recovered from the degraded signal by the AFL. The degraded signal is restored by the 3R regenerator with the Q -factor improved.

2) Cross gain compression (XGC) and saturable-absorber scheme

This scheme use XGC in an SOA to suppress the noise

at 1 level, and use saturable-absorber to suppress the noise at 0 level. The advantage is that this scheme does not convert the wavelength of the input signal, and is suitable for high speed bit-rate re-shaping. Based on XGC, 40-Gbit/s all-optical wavelength preserving 2R-regeneration transparent is demonstrated for both NRZ and RZ modulation formats [74]. Using XGC in the gain-saturated SOA and saturable-absorber, 10 Gbit/s wavelength-preserving 2R-regeneration is demonstrated by using 2 subsequent stages [75].

3) Self-phase modulation (SPM) effect in CQD-SOA

By properly filtering the SPM broadened output spectrum in a CQD-SOA can achieve regenerative amplification of short picosecond pulses, regenerative amplification of RZ signal up to 80 Gbit/s is demonstrated. This scheme works at low input power with large input dynamic range exploiting SPM with detuned filtering in a CQD-SOA [76].

4 Optical logic

Optical logic is essential for signal processing in the optical switching application, such as bit error monitoring [77], bit pattern recognition [78], label-swapping [79], optical packet address and payload separation [80], and optical routing decision [81]. Optical logic gates like AND, NOT, OR, XOR, NAND, and XNOR functions have been realized based on the nonlinearities of the SOA, such as XGM, XPM, XPolM, and FWM.

1) Optical logic gates using XGM

The configuration of all optical logic gates by using XGM is simple and efficient. A basic structure of NOT logic gate is shown in Fig. 8. This structure can be extended to implement XOR [82], NAND [83] and other logic operation. Due to the slow carrier recovery, it is difficult to realize high speed logic gate. The blue detuning filtering technology can be used to solve this problem.

2) Optical logic gates by using XPM or XPolM

XPM of SOA can transmit the phase modulation to intensity modulation and achieve all logic gates. The optical logic gates with SOA-MZI, terahertz optical asymmetric demultiplexer (TOAD) and DI structures

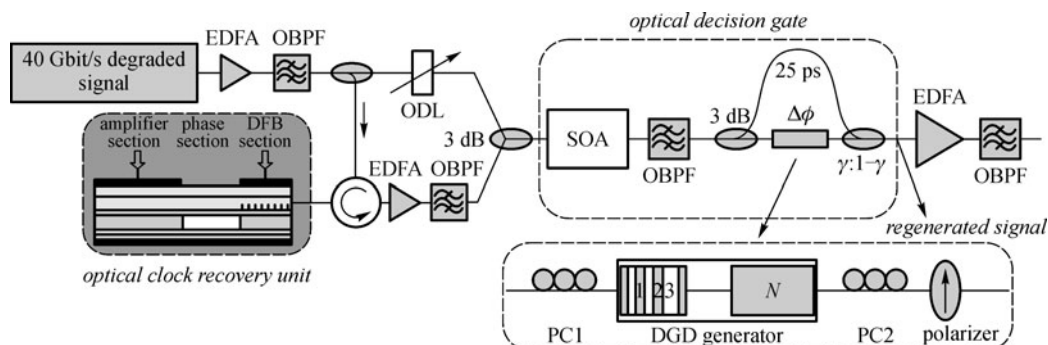


Fig. 7 Setup of 3R regenerator based on AFL and SOA-DI configuration

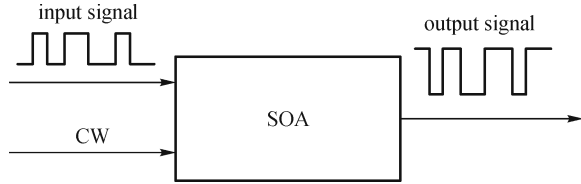


Fig. 8 Basic NOT logic gate based on XGM

have been extensively studied. XOR logic gate is obtained by using SOA-MZI [84], the results show that the extinction ratio in counter-propagation is 10 dB higher than that in co-propagation scheme. The next step for counter-propagation scheme is to improve the operation speed. 85 Gbit/s optical XOR logic gate is demonstrated by ultrafast nonlinear interferometers (UNIs) incorporating SOAs [85]. All-optical multi-logic gates with AND, OR, and XOR functions at 10 Gbit/s are demonstrated by using a single SOA assisted by optical filter [86], optical filter is detuned to select the specific components to realize different logic function.

By adjusting the polarization state of the input signal, 10 Gbit/s NOR and OR logic gate is demonstrated in an SOA by using XPolM [87].

3) Optical logic gates by using FWM

Optical logic gate employing FWM is attractive because it is transparent to signal format and bit rate, although FWM in an SOA still has a drawback of low efficiency. Based on FWM, polarization-shift keying (PolSK) modulated signals can be used to realize all optical logic gates. Reconfigurable 10 Gbit/s all-optical XOR, XNOR, AND, NOR logic gates are demonstrated by encoding information in the polarization of the input signals [88]. Since FWM effect in an SOA only arises when the pump and probe light have the polarization, reconfigurable logic gate can be realized by controlling the polarizations of the pump and probe. With the same principle, a 40 Gbit/s multi-function logic gate is proposed [89]. Cooperating the tunable filter and polarization beam splitter, XNOR, AND, NOR, XOR logic gates can be achieved.

Combining FWM with XGM and XPM, 40 Gbit/s multi-function optical logic gate is demonstrated [90]. The setup is shown in Fig. 9. This scheme can achieve AND, NOR, XNOR, NOT and OR in the same structure. Detuning optical filtering technology is used to enhance the recovery time of SOA, thus increase the operation speed. The scheme can be expanded for optical 2–4 encoders and comparators [90].

5 Optical format conversion

With the development in the optical networks, particularly in the high capacity long-haul transmission system, many advanced modulation data formats have been

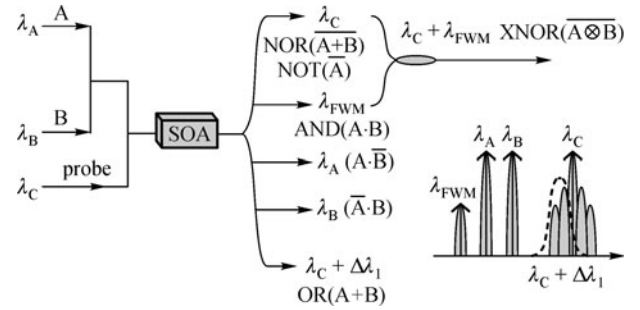


Fig. 9 Setup of multi-function logic gate

investigated, such as phase-shift-keying (PSK), binary phase-shift-keying (BPSK), differential phase-shift-keying (DPSK), differential quadrature phase-shift-keying (DQPSK), etc. Therefore, optical networks will have traditional on-off-keying (OOK) such as NRZ and RZ format, as well as the advanced modulation formats. Thus, optical format conversion becomes important to interconnect the two different networks in which different modulation formats are employed. Many solutions for format conversion have been proposed, we review some recent progress using SOA technology.

1) Converting between RZ and NRZ

Optical single-to-dual channel format conversion is demonstrated from NRZ to RZ using FWM in an SOA [91]. The original NRZ format is converted to RZ format by injecting a synchronized clock signal into the SOA. The format conversion is successfully implemented at bit rate of 20 and 40 Gbit/s, and all converted RZ signal have a Q -factor larger than 6. Multi-channel NRZ to RZ modulation format conversion is demonstrated using a single SOA based Sagnac interferometer [92]. Optimization of the control clock power results in the considerable improvement of receiver sensitivity and input power dynamic range to over 20 dB.

2) Converting between OOK to PSK

NRZ-OOK to RZ-BPSK conversion is demonstrated by using transient XPM in an SOA, 1.5 dB receiver sensitivity improvement is achieved for RZ-BPSK relative to baseline RZ-OOK [93]. 40 Gbit/s all-optical NRZ to PolSK format conversion is based on transient XPM using an SOA assisted by optical filtering [94]. An error-free all-optical 2×10.7 Gbit/s NRZ-OOK to 10.7 Gsymbol/s RZ-QPSK modulation format conversion is obtained using a novel developed integrated SOA three-arm-MZI wavelength converter module [95].

40 Gbit/s multifunction optical format conversion is proposed by using non-degenerate FWM in an SOA [96]. The scheme has the ability to achieve NRZ-OOK/DPSK/DQPSK to CSRZ-OOK/DPSK/DQPSK, RZ-OOK/DPSK/DQPSK to CSRZ-OOK/DPSK/DQPSK, and CSRZ-OOK/DPSK/DQPSK to RZ-OOK/DPSK/DQPSK format conversions. Finally, the BER measurements of some

10 Gbit/s operations are demonstrated to verify the proposed multifunction format conversion. The power penalty is less than 1 dB at the BER level of 10^{-9} .

6 Conclusion

We have reviewed some recent advances on SOA-based optical signal processing towards optical switching. Significant progress has been made during the past few years for increasing the operating speed to more than 100 Gbit/s and enhancing sophisticated functionality. In the near future, researchers are expected to pay further attention to some unique features such as phase-modulated signal processing, optical buffering, multi-channel operation, variable bit-rate capability, and simultaneous multiple functions, etc.

For optical switching application, it is essential for optical signal processing to be conducted in photonic integrated devices, thus high operating speed and stable operation can be achieved. Nowadays photonic integrated circuits (PICs) technology already enable a single photonic chip to contain many sophisticated passive and active devices, such as tunable lasers, coupler, arrayed waveguide grating (AWG) and optical wavelength converters [97]. For example, tunable laser can be integrated with SOA or electro-absorption modulator (EAM) using monolithically integration [98,99]. Another example is that the MOTOR monolithic chip contains more than 200 optical devices in a single $4.25\text{ mm} \times 14.5\text{ mm}$ chip [9]. Hybrid integration technology also allows large-scale photonic integration [100,101]. It is a trend that optical components are slowly migrating from manual assembly of discrete optical devices to automated, semiconductor wafer-processing techniques and single-chip solutions. Ultimately, the signal processing in major optical networks will be performed in the optical domain at high speed by using photonic integrated devices.

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