A Review On All Optical Circuits

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Abstract* - *Optical computation plays the major role in enhancing the speed, data transmission rate and processing power by replacing the electronic circuits with the optical circuits. All optical circuits are very efficient for high speed signal processing by performing digital computations through photons instead of electrons. This paper reviews the different technology of all-optical circuits in all optical processing from the basics to advanced logic gates to the extent of recent implementation in all optical signal processing. Various schemes in optical processing are discussed, compared and the future direction is outlined.

Index Terms— Optical Processing, Optical Computation.

I. INTRODUCTION

Optical signal processing is the key technology for making flexible and high speed photonic networks. The rapidly growing development of all optical processing systems, requires ultra compact and high speed all optical gates. Fast serial processing requires ultrafast logic gates, and the ultimate speed will be found in all-optical systems where the signals remain as photons throughout the system. All optical gates operations can be implemented by linear and non linear designs. The linear designs are based on the self collimation effect [1], multimode interference effect [2] and light beam interference effect [3, 4]. The non linear designs are based on fiber gratings [5,

6], semi conductor optical amplifiers (SOAs) [7], semiconductor micro resonators [8], periodically poled lithium niobate (PPLN) waveguides [9-12], and so on. A promising candidate among such nonlinear elements is the SOA having the practical advantages of high nonlinearity, low power consumption, short latency, high stability, and strong compactness. The non linear design based on SOA is classified into two categories. In the first category the non linear properties of SOA such as cross-phase modulation (XPM), cross-polarization modulation (CPM), cross- gain modulation (XGM), and four-wave mixing (FWM) is used in the design. In the second category the gates consist of SOA-assisted fiber Sagnac interferometer, ultra-fast nonlinear interferometer (UNI), SOA-assisted Mach-Zehnder interferometers (SOA-MZIs), and an SOA-assisted Michelson interferometer (SOA-MI).The limitation of conventional bulk SOA is the operation speed due to the slow temporal response of gain and phase recovery.On the other hand, the gain and phase recovery response is significantly faster in Quantum dot SOA (QD-SOA) compared to Quantum well (QW) SOA, which provide high-speed performance for QD-SOA based logic system [13]. The other methods for all optical logic gates are the photonic crystals based devices which can be used in both linear and non linear regimes. The development of all optical logic gates provides the data rate from 10 Gb/s to 1 Tb/s and the extinction ratio (ER) ranges from 6.5 dB to 30 dB. This paper reviews the different technologies used for implementing basic logic gates and the advanced all optical signal processing circuitries. The comparison based on different data rates and ER for various technologies is also analyzed.

This paper reports the review of all-optical circuits from the speed of 10 Gb/s to 1Tb/s. Introduction and review to all optical signal processing is presented in Section 1. The section 2 discusses the development of XOR gate using various technologies from 10 Gb/s to

250 Gb/s. Section 3,4 5 represents the development of NOR, XNOR and OR respectively. Finally the conclusion and future outline based on the review are made in section 6.

II. DEVELOPMENT OF XOR GATES THROUGH VARIOUS TECHNOLOGIES

All-optical exclusive-OR (XOR) is considered to be fundamental logic gate as it is receiving a lot of attention due to its great potential as an optical comparator and decision circuit. It can also perform a set of critical functionalities, such as label or packet switching, decision making, regenerating, basic or complex computing, pseudorandom number generating, parity checking, and so on [14]. XOR operation usually needs a nonlinear element to perform as a switching gate. Different nonlinear operations can be performed by the non linearity present in the SOA and optical fiber which includes FWM, XPM, CPM, XGM or the combination of all these.A promising candidate among such nonlinear elements is the SOA because of its high nonlinearity, low power consumption, short latency, high stability, and strong compactness. So far, many kinds of all optical XOR gates have been demonstrated, with operation speeds ranging from 2.5 to 1 Tb/s and output contrast ratios from 6.5 dB to approximately

30 dB. The design of XOR using non linearities in SOA include a 10 Gb/s XOR using CPM in SOA [14-15], a 10-40 Gb/s XOR using FWM [16-26], and a 10/ 40 Gb/s XOR using XGM [27-28]. Typical XOR gates by using SOA assisted interferometer structures include 40 /100 Gb/s XOR and 22 dB of (ER) using an SOA-assisted

fiber Sagnac interferometer [29-31], a 20 /40 Gb/s XOR and 6.5-11 dB of ER using UNI [32], a 10 /40 /160 Gb/s XOR and 30dB of ER using SOA-MZIs and a 10 /20 Gb/s XOR with 11 dB of ER ratio using an SOA-MI [33] and 80 Gb/s XOR with 13.9 dB of ER using SOA-MZI-DI [34]. Fiber-based XOR gates have been proven to be faster and pattern- insensitive but bulky in size, while compact SOA based ones suffer from the speed limitation induced by slow SOA gain recovery time. Those based on photonic crystal or active SOA waveguides with differential input schemes deserve more research attention. Practically, the XOR gates using interferometer structures are having brighter future due to their potential for integration. The fiber based interferometers are limited by instability whereas the utilization of integrated MZI using CPM in SOAs may suffer from additional noise and speed limitations (unless special high-speed SOAs are used), and someof the techniques require more than one SOA to achieve the XOR function .

A 10 Gb/s all-optical XOR gate using polarization rotation induced by the Kerr effect in a single 2-km highly nonlinear fiber (HNLF) was improved to 40

Gb/s by using return-to-zero differential phase-shift keying (RZ-DPSK) signals using FWM in SOAs. Since the Kerr effect is proportional to the fiber nonlinearity, by using HNLF with higher nonlinearity, both the output power and ER of the XOR gate can be improved considerably and the required input optical power can be decreased [35]. XOR utilizing fiber based nonlinear optical loopmirror (NOLM) has been demonstrated at 100

Gb/s [36], but this scheme is not easy to be integrated. XOR scheme based on UNI, or based on CPM in a SOA needs accurate control of polarization. The operation speed of XOR using terahertz optical asymmetric demultiplexer (TOAD) is limited by the carrier recovery time of the SOA. Implementation based on Sagnac interferometric structure has the advantages of structural simplicity, operation stability, polarization independency, high-speed operation, and integrated potential. Conventional techniques using SOA-MZI are limited by the gain and phase response time of SOA, which limits the operating speed to 20 Gb/s. A polarization maintaining loop (PML) mirror operates as a DI and can function as an “optical gate”. SOA and PPLN have the integration potential and offer several distinct advantages of ultrafast response, negligible spontaneous emission noise, low intrinsic frequency chirp, and complete transparency to bit rate and data format; however, they are intrinsically comprised: SOAs have free-carriers, leading to patterning effects for data rates of greater than 100 Gb/s; and PPLN has bandwidth limitations and requires precise temperature control [37-38]. Therefore, alternative platforms are of significant interest to circumvent these issues and allow the integration of these devices into real systems.

Nano photonic devices in highly nonlinear materials such as chalcogenide glasses (ChG) and silicon are key in reducing operating power requirements since they can achieve extremely high nonlinear parameters. The experiment establishes ChG waveguides for all-optical logic operations at datarates of up to Tbit/s with no patterning effect in [39]. The introduction of QD-SOAs provides ultra high speed optical switching of 250 Gb/s to 1Tb/s due to very fast gain and phase recovery response than QW-SOAs [40-41]. Fast phase change of a probe signal is also obtained by two-photon absorption (TPA) of a pump beam. The encryption process can be modelled using XOR gate based on TPA pump beam with the speed of 250 Gb/s [42]. Tag Comparison (TC) circuit, in order to decide upon a cache hit or cache miss operation, utilizes XPM based XOR logic gates based on SOA-MZIs, was demonstrated at 10 Gb/s for all 8 word channels with a total power penalty of 5.1 dB [43].

Table 1. Comparison between various technologies to implement XOR Gate

Sl. No	Technology	Operating speed	Extinction Ratio
1.	TOAD	10 Gb/s	11dB
2.	Non linear Loop mirror	10Gb/s	13dB
3.	Polarization maintaing loop mirror(PML)	80Gb/s	13.581dB
4.	HNLF	10-40 Gb/s	14-25dB
5.	UNI	5-40 Gb/s	6.5-11 dB
6.	Sagnac	40-100 Gb/s	15dB
7.	Michelson	10Gb/s	11dB
8.	Mach-Zehnder Interferometer	10-80Gb/s	11-15dB
9.	Delay Interferometer	80Gb/s	13.9dB
10.	Silicon nano wire	40Gb/s	20dB
11.	NRZ PolshK	40Gb/s	15dB
12.	InGaAs ring resonator	20Gb/s	11dB
13.	PPLN	20 Gb/s	14dB

III. NOR MODELS

The basic element for all optical signal processing is the optical decision gate and that can be used as the signal generator. NOLM provides improved ER by design NOR as switching gate but it requires very high input powers and are greatly dependent on signal polarization and fiber parameters. A wavelength tunable all optical decision schemes using SOA-DBR laser provides steep optical decision curves with improved ER [44].

The all-optical logic NOR function can be performed by two-cascaded SOA configuration with a high ER for a wider range of input and output wavelengths. Optical integrated techniques reduce the interconnection distance between the two-cascaded SOAs and used to evaluate the bit rate of the parallel configuration [45]. This parallel

SOA-MZI structure enables simultaneous operation of various logical functions. Maximum ER can be obtained by adjusting the optical gain and phase differences in SOA-MZI structures. The output pulses are reshaped with a high ER performance of better than 15dB and enables all-optical logic operations at high speed using XPM, which improves the performance and integration capability. The NOR gate can also implemented by Injection based Laser method [46], Photonic logic gate with non linear interferometric structure [47], NRZ Polarization shift keying, Saturable absorber etalons [48] and its comparison with operating speed and ER is given in Table 2.

IV. XNOR MODELS

XNOR function can be optically implemented by exploiting FWM and XGM in an SOA. Implementation based on a parallel SOA uses tricky interferometric configurations. Using single SOA avoids this issue by adjusting the probe signal to ON and OFF, so that it achieves different gates and reconfigurability. Introducing a counter-propagating continuous-wave (CW) light reduces the SOA response times and increasing the maximum bit rate of the signals [49]. XNOR gates can also be realized based on FWM in an SOA and encoding information in the polarization of the input signals. In this, due to the constant intensity nature of the signal, pattern-dependent degradation can be reduced and by adjusting the polarization controllers at the input and output in this SOA-based device. Even though the device is quite simple, it can generate several logic functions by merely adjusting the polarization controllers at the input and output [20].

Logic gates based on FWM in SOAs using the broad-band model with the Polarisation Shift Keying (PolSK) modulation format is free of pattern effect and achieves simple logic gates including XNOR and also complex logic gates including half adder, half subtractor, decoder and comparator [22]. The ultra- fast optical logic gate device by monolithically integrating a single QD-SOA with FWM, XGM and ring resonators realize XNOR and other logic functions and demonstrate the potential of ultra-fast operation with 160 Gb/s RZ signals by the simulation using transfer matrix method (TMM) [50]. MMI- based waveguide structure supports large bandwidth and data transfer rate and it is a promising method for preventing power loss occurring in idle output ports, and also for compact integration with low power consumption [51].

V. OR MODELS

An OR gate based on XGM effect in a single SOA has a simple configuration but low extinction ratio and relatively large chirp, whereas OR Logic gates based on XPM own advantages of high extinction ratio at the cost of complex interferometer configurations.

Table 2. Comparison between different logic gates

Technology	Gate	Operating speed	ER
TOAD	XOR	10 Gb/s	11 dB
Sagnac Interferometer	XOR	40 -100 Gb/s	14.6 dB to >15dB
Electro Absorbtion Modulator Using Phase Modulation	AND	10 Gb/s	>10 dB
SOA-XGM	NOR, XOR	10 Gb/s	11-12 dB
SOA-MZI	XOR,NOR,OR ,NAND	20 , 40 and 80 Gb/s	15.5 dB
Micro Ring Resonators	NAND, AND	30 Gb/S, 160 Gb/s	19.5 dB, 20 dB
Kerr Effect in HNLF	XOR	10 Gb/s	25 dB
XPM in HNLF	XOR, AND, OR	10 Gb/s	14.0 dB (XOR), 22.2 dB (AND), and 16.5 dB(OR)
Non Return to Zero Polarization Shift Keying	AND, NOR, XNOR, XOR,	40 Gb/s	15 dB
FWM In InGaAsp/Inp Ring Resonator	AND	40 Gb/s	10 dB
Two Parallel SOA-MZI	XOR, NOR, OR, NAND	10,20,40 Gb/s	15 dB
Fiber Optical Parametrical Amplifier	XOR, OR, NOT and AND	10 Gb/s	XOR- 1.6 dB, OR- 2.6 dB, NOT- 1.2 dB, and AND--1.1 dB
Non Linear Polarization Rotaion in SOA and Red Shifted Sideband Filtering	OR	20Gb/s	10.1dB
Fiber Non linearity in Optical Loop Mirror	XOR, OR,NAND,NOR,NOT	40 – 160 Gb/s	9.85 – 14.68 dB
Differential Interferometer	AND, NOR	20 Gb/s	10 dB
Single Mode Fabry Perrot Laser Diode	NAND, AND	10 Gb/s	14.6 dBm(NAND), 12.5 dBm(AND)
UNI	Basic Gates	10- 40 Gb/s	5- 40 dB
Tunable All Optical Decision Scheme Using SOA Integrated With Distributed Bragg Reflector Laser	NAND, NOR	1.25 and 10Gb/s	28-6 dB and improved to 24-20dB
Multimode Interference Waveguide With Beam Propogation Method	XNOR, NAND, OR, XNOR, NOT	40 Gb/s	XNOR-26dB, NAND-24.7dB, OR-25.9dB, XNOR-26dB, NOT-25dB

The nonlinear polarization rotation (NPR) in SOA is also a very important effect for implementing an OR logic gate without the need of interferometer configuration and provide strong saturation of amplifier gain In three dimensional beam propagation methods, the finite element method and the finite difference methods can be analyzed respectively for discretizing the fiber cross section and the propagation direction. 3-D geometry consisting of optical fibers and a nonlinear film based on the Crank–Nicholson finite element method provides the functionality of OR gate and the other basic logic gates [52]. All-optical logic gates by using multibranch waveguide structures with localized optical nonlinearity uses the beam propagation method to simulate the all-optical logic devices and find the optimized parameters to perform the logic functions [53]. The logic functions can also be realized using electro-absorption modulator (EAM) and intensity dependent frequency shifting self phase modulation (SPM). An optical multi level modulation can be realized by adjusting the center frequency of an optical band-pass filter in the logic gate. It provides an error free, polarization independent operation and long time stability [54].

A novel all-optical logic OR gate based on Non linear polarization Rotation NPR in SOA with red-shifted filtering has a simple configuration and allows photonic integration with ultrafast signals [57]. . The operation speed of all the above schemes is limited by the slow carrier's recovery time of SOA. OR gates can also be realized based on photonic crystals structure and is expected that such designs have the potential to be key components for future photonic integrated circuits due to their simplicity and small size [55].

CONCLUSION

All optical logic circuits are very efficient for high speed signal processing by performing digital computations. This paper reviews the optical circuits for the basic gates. The different gates are designed using different non linearity and different modulation techniques. It shows excellent performance for all optical signals processing without deteriorating the quality and power of the signal. The limitation of optical computing is found that the extinction ratio are still superior in digital gates compared to all optical designs. The Table 1 and 2 represents the various technologies in terms of operating speed and ER in all-optical signal processing. All optical computing is an exciting field where we can expect much innovation in different optical circuits operating at ultra high speed.

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