Optik 122 (2011) 1486–1491

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Eliminating the additional input beam in all-optical XOR gate using Terahertz Optical Asymmetric Demultiplexer (TOAD) based interferometer: A theoretical analysis

Tanay Chattopadhyay*

Mechanical Operation (Stage-II), Kolaghat Thermal Power Station, WBPDCL, Mecheda, Purbamedinipur, KTPP Sub Post Office, 721137 West Bengal, India

ARTICLE INFO

Article history:
Received 23 March 2010
Accepted 5 September 2010

Keywords:
Optical switching
Binary XOR operation
Terahertz Optical Asymmetric Demultiplexer (TOAD)
Polarization

ABSTRACT

All-Optical XOR Logic is a key technology for performing a set of operations in optical time division multiplexing (OTDM) multi-access network. In this paper an All-Optical Boolean XOR logic gate with Terahertz Optical Asymmetric Demultiplexer (TOAD) based interferometric switch is designed and described. In this proposed XOR gate, no additional input light source is used. Numerical simulation is also presented, which verifies the theoretical results. Contrast ratio, extinction ratio, amplitude modulation, bit error rate and signal to noise ratio values have also been analyzed.

1. Introduction

All-optical signal processing concepts and technologies have evolved remarkably in the past few years chiefly due to the discovery of semiconductor based all-optical switches. The cumbersome, complex and power consuming optical–electrical–optical (O–E–O) conversion is avoided in all-optical signal processing. All-optical Boolean XOR gate is the core logic unit to implement various all-optical systems such as binary adders, binary counters and decision circuits, as well as encoders and bit-pattern recognition circuits. A revolution has been brought about in all-optical information processing systems with the help of the discovery of ultra high speed all-optical switches based on cross phase modulation (XPM) [1–5]. Various schemes of all-optical XOR operation have been reported using semiconductor optical amplifier-Mach–Zehnder interferometer (SOA-MZI) [6–13], Terahertz Optical Asymmetric Demultiplexer (TOAD) based interferometric switch [14,15], four wave mixing (FWM) in a SOA [16], ultrafast nonlinear interferometer (UNI) [17–19] and bismuth oxide based nonlinear fiber (Bi-NLF) [20].

However, all the above mentioned XOR gates have used additional input beam such as clock signal or continuous wave (CW) light along with the two input beams in their circuits. Synchronization is a hurdle in case of cascading of these typical circuits in large scale integration because of different source of light for each gate. Recently XOR gate based on only two input beams was reported by Soto et al. [21], Kim et al. [22] and Li et al. [23,24]. In this present paper an all-optical XOR gate using Terahertz Optical Asymmetric Demultiplexer (TOAD) based interferometric switch is designed and described where the additional input light source is excluded. Numerical simulation result (with the help of Mathcad-7.0) confirms the theoretical results. In this present paper, the binary logical states (0, 1) are represented by no light (null) and vertically polarized light (↕), respectively.

2. TOAD based all-optical switch

TOAD is all-optical switch (shown in Fig. 1), which can operate at frequencies in terahertz range [2,3]. It uses a semiconductor optical amplifier (SOA) that is asymmetrically positioned in the fiber loop. The switch is essentially a fiber loop jointed at the base by an optical 50:50 coupler, which splits the incoming signal into two equal parts that counter propagate around the loop and recombine at the coupler. In almost all TOAD discussed by many authors, the transmitting mode of the device (output port) is used to take the output signal. But the signal that exits from the input port (reflecting mode) remains unused. In this present communication we have tried to take the output from both the transmitting and reflecting mode of the device. The output power at transmitted (T) & reflected

* Tel.: +91 9432075035; fax: +91 3228231256.
E-mail address: tanay2222@rediffmail.com

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doi:10.1016/j.ijleo.2010.09.033

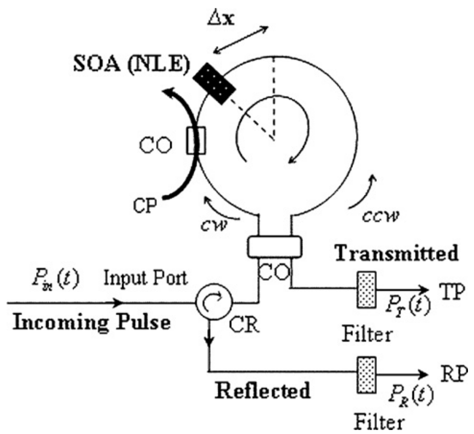

Fig. 1. All-optical TOAD based interferometric switch. CP: control pulse, Filter: polarization filter which blocks the CP, CO: (ideally 50:50) 2 × 2 3 dB coupler, SOA: semiconductor optical amplifier, RP: reflected port, TP: transmitted port. Here incoming and CP are orthogonally polarized light.

(R) port can be expressed as [25–30]:

$$P_T(t)=\frac{P_{in}(t)}{4}\cdot\{G_{cw}(t)+G_{ccw}(t)-2\sqrt{G_{cw}(t)\cdot G_{ccw}(t)}\cdot\cos(\Delta\varphi)\} \tag{1}$$

$$P_R(t)=\frac{P_{in}(t)}{4}\cdot\{G_{cw}(t)+G_{ccw}(t)+2\sqrt{G_{cw}(t)\cdot G_{ccw}(t)}\cdot\cos(\Delta\varphi)\} \tag{2}$$

where $G_{cw}(t)$, $G_{ccw}(t)$ are the power gain and the phase difference between *cw* and *ccw* pulse $\Delta\varphi = -\alpha/2\ln(G_{cw}/G_{ccw})$, α is line-width enhancement factor. When a strong control pulse of is injected into the loop (CP = ON), it saturates the SOA and changes its index of refraction. As a result, the two counter-propagation data signal will experience a differential gain saturation profiles i.e. $G_{ccw} \neq G_{cw}$. Therefore, they recombine at the input coupler, and then $\Delta\varphi \approx -\pi$ the data will exit from the transmitted port and $P_R(t) \approx 0$. In the absence of a control signal (CP = OFF), the incoming signal enters the fiber loop, pass through the SOA at different times as they counter-propagate around the loop, and experience the same unsaturated amplifier gain G_0 of SOA, recombine at the input coupler i.e. $G_{ccw} \approx G_{cw}$. Then, $\Delta\varphi \approx 0$. So expression for $P_T(t) \approx 0$ and $P_R(t) \approx P_{in}(t)\cdot G_0$. It shows that data is reflected back toward the source. We consider here that the SOA is polarization independent.

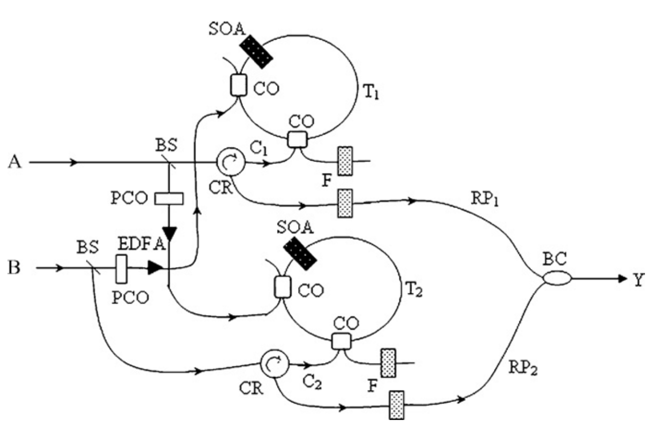

Fig. 2. All-optical Boolean XOR circuit. CO: (ideally 50:50) 2 × 2 3 dB coupler, PCO: polarization converter, T_1 and T_2 are two TOAD based interferometric switches, BC: beam combiner, BS: 50:50 beam splitter, EDFA: Erbium Doped Fiber Amplifier, RP: reflected port.

Table 1
Truth table of Boolean XOR gate.

Inputs		Output
A	B	Y
0	0	0
0	1	1
1	0	1
1	1	0

A polarization filter (F) may be used at the output to reject the control and pass the incoming pulse. Here we use vertically polarized light (↕) as incoming signal and horizontally polarized light (●) as control signal. 'F' is basically a polarizer isolator, which blocks horizontally polarized light (●) and passes vertically polarized light (↕). The Jones matrix of 'F' is $\begin{pmatrix}0&0\\0&1\end{pmatrix}$. Mathematically it can be expressed as:

$$\begin{pmatrix}0&0\\0&1\end{pmatrix}\begin{pmatrix}0\\1\end{pmatrix}=\begin{pmatrix}0\\1\end{pmatrix}\quad\text{and}\quad\begin{pmatrix}0&0\\0&1\end{pmatrix}\begin{pmatrix}1\\0\end{pmatrix}=\begin{pmatrix}0\\0\end{pmatrix}$$

Now it is clear that in the absence of control signal, the incoming pulse exits through input port of TOAD and reaches to the reflected port (RP) as shown in Fig. 1. In this case no light is present in the transmitted port (TP). But in the presence of control signal, the incoming signal exits through transmitted port (TP) as shown in Fig. 1. In this case no light is present in the reflected output (RP). In the absence of incoming signal, TP and RP receive no light as the polarizing filter blocks the control signal.

3. Principle of operation

The operation of the TOAD based XOR gate can be described with the help of Fig. 2. Here Two TOAD based switches (T_1 and T_2) are used to design XOR gate. Light from input 'A' and 'B' are directly connected to TOAD-based switches T_1 and T_2 to act as incoming signals. One part of the input 'A' and 'B' are also connected to switches through polarization converter (PCO) and EDFA (Erbium Doped Fiber Amplifier) so that they can act as control signals as shown in Fig. 2. The Jones matrix of the polarization converter or 'PCO' ($\lambda/2$ plate with azimuth angle θ with the optical axis) is $M_{\lambda/2}(\theta)=\begin{pmatrix}\cos 2\theta & \sin 2\theta\\ \sin 2\theta & -\cos 2\theta\end{pmatrix}$. Here we chose $\theta = 45^\circ$, such that vertically polarized light (↕) converts into horizontal (●) one and vice versa, when it passes through it. Mathematically it can be expressed as:

$$\begin{pmatrix}0&1\\1&0\end{pmatrix}\begin{pmatrix}0\\1\end{pmatrix}=\begin{pmatrix}1\\0\end{pmatrix}\quad\text{and}\quad\begin{pmatrix}0&1\\1&0\end{pmatrix}\begin{pmatrix}0\\1\end{pmatrix}=\begin{pmatrix}1\\0\end{pmatrix}$$

Hence control and incoming pulse can be made two types of orthogonally polarized light. Now the reflected ports (RP) of the switches T_1 and T_2 (RP_1 and RP_2) are combined at beam combiner (BC) to get final output 'Y'. The truth table of XOR operation is shown in Table 1.

Case-I: When A = B = 0 i.e. incoming signals of two TOAD based switches T_1 and T_2 are absent. Hence no light is received at the output port 'Y'.

Case-II: When A = 0, B = 1 i.e. incoming signals of T_1 and control signal of T_2 are absent. Only incoming signal of T_2 is vertically polarized light (↕). Hence according to the switching principle of TOAD based switch discussed in Section 2 we find that RP_2 = 1 (↕). Hence at output 'Y' = 1.

Case-III: When A = 1, B = 0 i.e. incoming signals of T_2 and control signal of T_1 are absent. Only incoming signal of T_1 is vertically polarized light (↕). Hence according to the switching principle of