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Analytical approach of developing wavelength encoded AND, NAND and X-OR logic operations and implementation of the theory using semiconductor optical amplifiers

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ABSTRACT

Frequency encoding technique is a very promising and faithful technology for very fast long-haul optical communication and super fast computation. Implementation of different logic gates based on the principle of frequency conversion is the key mechanism of frequency encoded data processing and networking. It is established that semiconductor optical amplifiers (SOA) have been used successfully for the purpose of frequency conversion. One of the important techniques of frequency conversion is the conjugate beam generation by four wave mixing (FWM) in SOA and ultimately conversion of it into desired frequency by means of reflecting semiconductor optical amplifier (RSOA). However the efficiency of conjugate beam generation is restricted by polarization dependent gain saturation of SOA. This dependency can be successfully removed using polarization diversity scheme. Another technique of the frequency conversion is based on nonlinear rotation of the state of polarization of the linearly polarized probe beam. An important advantage of using polarization rotation in SOA is that a small change in rotation of the state of polarization will lead to a large difference in output power. Here in our present communication we propose a method of developing wavelength encoded AND, NAND and X-OR logic operations exploiting the above mentioned functions of SOA. For this purpose we have developed an analytical treatment based on which above mentioned three logic gates are conducted. The satisfactory simulation result proves also the validity of the developed theory.

1. Introduction

Ever increasing demand for faster and reliable data processor gives rise to the concept of optical computer. All-optical logic gates serve the main functions in realizing this optical computer. Several designs for optical logic gates have been proposed so far, however many of these are complex in architecture and slower in speed. In most of the optical data communication networks the states of information in binary system, i.e. the '0' state and the '1' state are generally encoded either by intensity encoding or by polarization coding or by phase encoding, etc [1–3]. In intensity encoding the presence of optical signal has been encoded as '1' state and absence of optical signal as '0' state. In case of long distance communication intensity of optical signal may fall and dropdown below the reference level and for which it may be treated as the '0' state of the signal which can lead to the bit error problem. In polarization encoding a certain state of polarization of the optical beam is encoded as '0' state and another orthogonal state of polarization is treated as '1' state [3]. Again the states of polarization may change for several causes which can also lead to the bit error in information processing. The problem can fully be solved, if one can encode and decode two different states of information (1 and 0) by two different frequencies [4–6]. It is known that if 1 and 0 logic states are encoded by two different frequencies then one may ensure about the state of a signal during transmission. That is if '1' state is encoded by the frequency 'ν_2' and the '0' state by 'ν_1' then ν_2 and ν_1 will remain unaltered through out the transmission of data, whether it suffer from reflection, attenuation loss, refraction, etc.

The authors at first established the new concept of implementing inversion logic operation by frequency encoding technique [4]. In this inversion operation system executed 2ν frequencies (1) from a ν frequency (0) signal and a frequency ν (0) signal from a 2ν frequency (1) signal. To develop these we have used the second harmonic generation and wave mixing properties of some nonlinear media. Using the same encoding/decoding technique the authors

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have contributed a paper of different logic operations based on Periodically Poled Lithium Niobate waveguide (PPLN) [5]. But the appropriate tuning for phase matching to achieve the desired second harmonic generation is difficult as well as conversion efficiency of second harmonic generation is very low. Again two optical signals of frequencies ν and 2ν (here $\nu = 1064$ nm and $2\nu = 532$ nm) can never propagate equally well inside the same optical fibre.

In Boolean logic based implementations of gates the states of information are only two. These limitations restrict the high speed processing of digital information and also restrict the parallel communication with wide range of information. On the other hand in contrast to the Boolean system, in multivalued system such as tristate system and quaternary system, states of information are more than two. Therefore the authors have contributed a new concept of conducting very high speed inversion (NOT) logic operations with tristate logic exploiting the highly efficient cross gain modulation (XGM) and wavelength conversion property of bulk RSOA, which is independent of polarization, insensitive to the wavelength of the input data provided it is within SOA gain bandwidth [6]. Here input states of a tristate logic system are 1, 0, and $\bar{1}$. In tristate system the laser pump beam of frequency ν_1 is encoded as state '1', pump beam of frequency ν_2 as the state '$\bar{1}$' and pump beam of frequency ν_0 as the '0' state. Here add/drop multiplexers (ADMs) perform the role of filtering as well as it amplifies the signal of reflected frequency. Therefore no further amplifier is required to amplify it before using it for next stage. Three frequencies have been selected in C band so that all three beams can propagate well inside a single cable. Here only one input signal frequency is present at a time and this frequency can easily be converted to another appropriate frequency using ADM and RSOA. But the problem arises when any two input signal operations are desired. For implementing two input different signal frequency logic operations, such as AND and NAND logic, it is not possible to convert two input signal frequencies to another appropriate frequency at the same time. But these two frequencies can be converted to a single frequency by phase conjugation mechanism exploiting nonlinear character of SOA and subsequently converting it to desired frequency using frequency converter (RSOA or SOA). Conjugate beam may be generated in many possible ways such as sum and difference wavelength generation by PPLN or using SOA. In our present communication the authors propose a method of developing a frequency encoded AND, NAND and X-OR logic gates exploiting frequency conversion properties of SOA. For this purpose the authors have enjoyed the facilities of the established standard method of conjugate beam generation technique by SOA which is polarization insensitive phase conjugation [7,8]. Our prime objective is wavelength routing to different appropriate channels and conversion from one wavelength to other appropriate wavelength. For this purposes we have used wavelength conversion properties of RSOA and nonlinear polarization rotation properties of SOA. Here the authors also have developed an analytical treatment of wavelength encoded AND, NAND and X-OR logic operations and simultaneously presented the simulation results of these logic operations in tabular form as well as graphically. For this purpose we encode/decode the state of information '0' by the beam of wavelength λ_1 (1530 nm) corresponding to frequency ν_1 and the state of information '1' by the wavelength λ_2 (1551 nm) corresponding to frequency ν_2. The truth tables for wavelength encoded AND, NAND and X-OR logic gates are shown in Table 1a–c.

2. Principle of operation of AND, NAND and X-OR logic gates

The operation of wavelength encoded AND, NAND and X-OR logic gates is based on four basic principles as

Table 1
Truth tables of wavelength encoded (a) AND, (b) NAND and (c) X-OR logic gates.

A	B	*Y*
(a) AND logic		
$\lambda_1(0)$	$\lambda_1(0)$	$\lambda_1(0)$
$\lambda_1(0)$	$\lambda_2(1)$	$\lambda_1(0)$
$\lambda_2(1)$	$\lambda_1(0)$	$\lambda_1(0)$
$\lambda_2(1)$	$\lambda_2(1)$	$\lambda_2(1)$
(b) NAND logic		
$\lambda_1(0)$	$\lambda_1(0)$	$\lambda_2(1)$
$\lambda_1(0)$	$\lambda_2(1)$	$\lambda_2(1)$
$\lambda_2(1)$	$\lambda_1(0)$	$\lambda_2(1)$
$\lambda_2(1)$	$\lambda_2(1)$	$\lambda_1(0)$
(c) X-OR logic		
$\lambda_1(0)$	$\lambda_1(0)$	$\lambda_1(0)$
$\lambda_1(0)$	$\lambda_2(1)$	$\lambda_2(1)$
$\lambda_2(1)$	$\lambda_1(0)$	$\lambda_2(1)$
$\lambda_2(1)$	$\lambda_2(1)$	$\lambda_1(0)$

(i) Phase conjugated beam generation in semiconductor optical amplifier.
(ii) Wavelength routing by means of optically add/drop multiplexers.
(iii) Wavelength conversion using RSOA.
(iv) Wavelength conversion using the rotation of the state of polarization of the probe beam in SOA.

2.1. *Phase conjugate beam generation in semiconductor optical amplifier*

SOA can be used as an important wavelength converter exploiting the coherent nonlinear process occurring in an SOA between the two optical fields, a strong pump beam 'A' and a weaker signal beam 'B' (or probe beam) [7–12]. In polarization diversity scheme, the conjugate beam is generated by the method of four wave mixing (FWM) which is polarization insensitive. In this scheme the states of input pump beams in both SOA1 and SOA2 are orthogonal to each other. The state of polarization of signal beams in each SOA is also parallel to pump beam in each SOA1 and SOA2. The mixture of pump beam of wavelength 'λ_A' and signal beam of wavelength 'λ_B' in SOA produces conjugate signal 'C' with the same state of polarization. When the orthogonal polarized counter-propagating conjugate signals from two SOAs are combined, the nonlinear interaction between them gives rise to a conjugate beam of wavelength $\lambda_C = (2\lambda_A - \lambda_B)$. The scheme will be polarization independent wavelength conversion efficiency provided both the SOAs have same gain and conversion efficiency. The process of conjugate beam generation is shown in Fig. 1(a) whereas the polarization direction of A and B is shown in Fig. 1(b) and the spectrum of λ_A, λ_B and λ_C is shown in Fig. 1(c).

To obtain the desired phase conjugate beam the polarizer P_A is used at the input pump beam terminals A such that pass axis of P_A is oriented at an angle 45° with respect to the axis of the 1st polarization beam splitter (PBS_1). The input signal polarized beam B may have any state of polarization (random). Both the input beams in PBS_1 will split up into TE and TM components so that input beam at SOA1 and SOA2 become $A_{TE} + B_{TE}$ and $A_{TM} + B_{TM}$ respectively. The mixture of $A_{TE} + B_{TE}$ in SOA1 will generate conjugate signal having TE state of polarization. Similarly mixture of $A_{TM} + B_{TM}$ in SOA2 will produce conjugate signal having TM state of polarization. When these orthogonal polarized conjugate signals from two SOAs are combined by means PBS_2, the nonlinear interaction between them gives rise to a converted beam of wavelength $\lambda_C = (2\lambda_A - \lambda_B)$ in addition with unconverted beam of wavelength λ_A and λ_B. We designate the conjugate beam generator unit as CBGU in our present communication.