# All optical phase encoded NOR logic gate implementation by four wave mixing in semiconductor optical amplifier

Sutanu Kumar Chandra

*Abstract*— **Increasing demand of high speed in data and image processing; optical computing has been proved its inevitability through its inherent properties. Different logic gates are the essential part of the processing unit. Semiconductor optical amplifier properties have created a new interest in the field of construction of the all optical logic gates with various encoding techniques. Phase encoding drew more attention to the researchers as it shows extended tolerance limit in long-haul fiber transmission system with higher receiver sensitivity. Thus phase encoding gives high spectral efficiency in optical computing and communication both. Four wave mixing (FWM) in semiconductor optical amplifier (SOA) is an intra band non linear process so it requires very short switching time. Thus phase encoding with FWM in SOA for the construction of the all optical logic processor gives very high-speed operation. Some optical logic gates already proposed and demonstrated experimentally by some research groups using phase encoding with the help of FWM in SOA. Here in this communication the author has reported a novel scheme of all optical phase encoded NOR logic gate with the uses of FWM in SOA.**

*Keywords*— **SOA, FWM, CMZI, NAND, Phase modulator, Phase shifter and Optical logic gate.**

## I.    Introduction

All optical signal processing has been receiving more and more attention due its lots of advantage over electronics (1)-(2). The everyday's growing need of high speed in computing cannot be fulfilled by electronic processing. The development of high performance processor in electronics is hampered by the Von Neumann bottleneck problem. The inherent properties of optics have been used to overcome this limitation in computing procedures. Optical processing techniques have been developing in a very fast rate throughout the world. All the elementary logic gates are the basic components of a digital processor. So the simple design of optical logic gates must be very necessary for the development of fast optical processor. In last few decades all the optical logic gates have been already proposed and demonstrated experimentally using different linear and non-linear optical properties of the material by many group of researchers (3)-(6),(12)-(15).

Recently semiconductor optical amplifier has been proposed extensively for developing different types of all optical logic gates due to its immediate response character, low power consumption and simple fabrication technologies in photonic integrated circuit. Several encoding and decoding methods has already been implemented for this development of fast optical logic gates with high efficiency. Some phase encoding schemes have been generating new interest in this research area due of its higher receiver sensitivity and improved nonlinearity tolerance of the fibre used in communication(7)-(10). Thus phase encoding formats is giving high spectral efficiency in optical computing. Again four wave mixing in SOA is a nonlinear intra-band process. So it requires a very small scattering time. So to develop the high performance optical computer it should be better to choose the fast optical switching techniques as FWM in SOA. Thus the optical computing by the phase encoding with FWM in SOA gives high speed with high transparency. Optical logic gates with phase encoded formats have been already demonstrated by some research groups using wave mixing techniques in semiconductor and other materials(12)-(15),(18),(19).  In this paper the author has proposed a novel scheme of all optical NOR logic gate using phase encoding formats with the help of FWM in SOA.

## II.    Encoding/Decoding technique

### A.    *Theory of Encoding*

In optical signal processing all the characters of light wave have been exploited in various encoding/decoding methods. To implement the very much efficient and fast optical logic processor, many encoding techniques have been used by different groups of researchers throughout the world. But every encoding scheme has special advantages with some limitation. In this proposed scheme a light signal can be called a '0' bit if it has no phase difference with respect to a reference light signal whereas a signal can be called '1' bit if it ensures a 'π' phase change with respect to the same reference signal. Due to stability in periodicity of phases in this encoding scheme, the output phase difference value $2n\pi$ and $(2n\pm1)\pi$ are equivalent to 0 and π phase difference respectively (where n is any integer).

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## B. *Arrangement of Interferometer for Phase Encoding*

In this proposal an arrangement of interferometers has been considered for choosing inputs and creates phase information according to the bits. Here two Mach-Zehnder interferometers are coupled by joining their single arm [9]. This arm is known as common arm and the arrangement Coupled Mach-Zehnder Interferometer (CMZI). In this CMZI, a light wave is first split equally by 1→2 Y-branch coupler (1:1) and then entered into the upper and lower input of it where these signals is again divided by 1→2 coupler splitters and transmitted through both the arms of upper and lower MZI. The light beams are combined by means of interference of the waves present at the upper and lower outputs of the CMZI by the 2→1combiner coupler. The interference will be constructive or destructive based on the phase of the light beams by which they meet with one another at that instant. In case of constructive interference, the light beam will come out with the same phase and frequency by which they interfere with one another and no light will emerge for destructive interference.
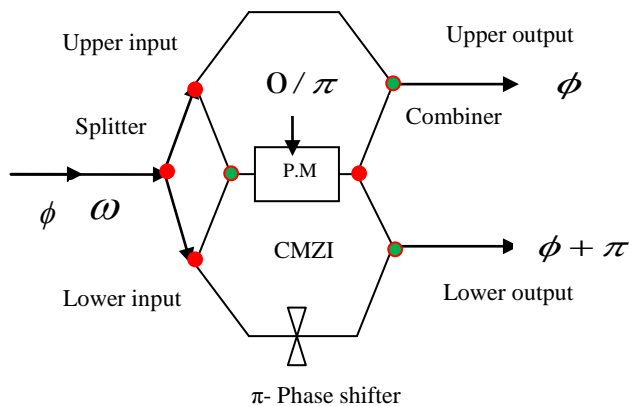


Fig-1:- The arrangement of CMZI with the outputs.

In this procedure a phase modulator (P.M) is placed over the common arm of the CMZI and which will introduce extra $\pi$ phase depends on the biasing voltage.

TABLE I.  NATURE OF THE LIGHT WITH PHASE AT THE OUTPUTS OF CMZI

| Initial phase of the light beam | Binary inputs | additional phase introduced by the phase modulator | Phase of light wave emerges from the upper outputs of the CMZI. | Phase of light wave emerges from the lower outputs of the CMZI. |
|---|---|---|---|---|
| | 0 | 0 | $\Phi$ | Absence of light |
| $\Phi$ | 1 | $\pi$ | Absence of light | $\Phi + \pi$ |

This phase modulator (PM) is enabled or disabled in accordance with the binary input signals by applying the voltage $V_\pi$ over it. A $\pi$ phase shifter is also inserted in the lower arm of the CMZI for selecting the light wave with proper phase at the suitable outputs required for this design of logic realization. The presence and absence of light wave with the phase at the outputs of the CMZI is shown the figure-1 and table-1

## III. **Principle of Self Pumped Four Wave Mixing in SOA**

FWM is a nonlinear intra-band process in a semiconductor optical amplifier. The phenomena of FWM takes place inside SOA when more than one light signal with different frequency enters within it and as a result of FWM in SOA it will generate many idler signal light waves of different amplitudes, frequencies and phases. When two light waves go into the inside of SOA instead of three, then both the input signal also acts as pump waves (12)-(13),(16). This is known as self pumped FWM and its output has the form given by,

$$E_{3,4}[FWM] = \eta\,(i,j)\,E_{i,j}E_{j,i}^2\,Cos[(2k_{j,i} - k_{i,j})x - (2\omega_{j,i} - \omega_{i,j})t + (2\phi_{j,i} - \phi_{i,j})]\,,$$

where $\eta(i,j)$ is the conversion factor in this process. Where we consider all the beams ( i,j = 1,2 ) be moving along the x axis with intensities $E_{i,j}$, frequencies $\omega_{i,j}$ and phases $\phi_{i,j}$ respectively. For an efficient FWM in SOA, all these waves are co-polarized. Therefore there are two simultaneous FWM outputs with frequency $\omega_3 / \omega_4 = (2\omega_1 - \omega_2) / (2\omega_2 - \omega_1)$ and phase $\phi_3 / \phi_4 = (2\phi_1 - \phi_2) / (2\phi_2 - \phi_1)$. The self pumped four wave mixing is shown in Fig. 2. Thus the self pumped FWM between two pump waves produce two side-bands with the unmodified pump beams.
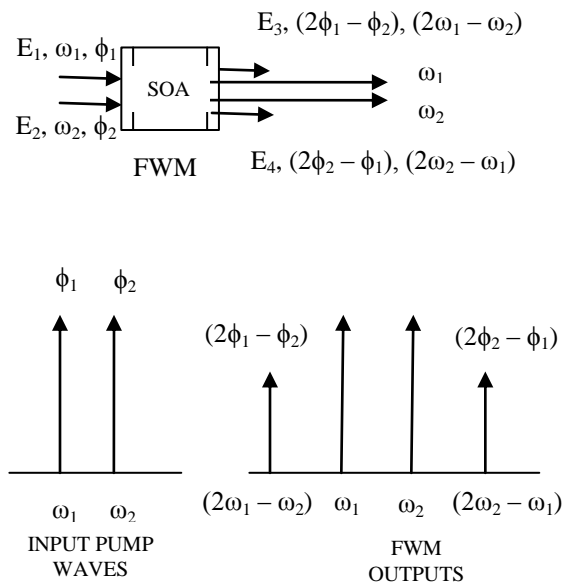


Fig.2. Self pumped FWM in SOA

# IV. **Proposed scheme of optical NOR logic gates**

In this scheme of logic gates two CMZI arrangement have used for introducing the additional phase based on the two binary inputs A and B simultaneously. When the binary inputs A or B = 0, then the light wave will come out with the same initial phase from the upper output whereas if A or B = 1, then the light wave will appear only from the lower output with $\pi$ phase extra over the initial phase from both the CMZI-1 and CMZI-2(11),(17)-(19).In this two cases no light will emerge from the lower and upper output respectively from both the CMZI-1 and CMZI-2. Here any two light waves with slightly different frequency $\omega_1$ and $\omega_2$ (nearly zero dispersion wavelength i.e.1550 nm) are used to produce the two phase encoded pump beams through CMZI and which are synchronously injected with proper phase inside SOA for FWM to implement the logic. Here four SOA (**S-1, S-2, S-3 and S-4**) are utilized for four combination of operation of the two input binary logic gate. For two wave supported self pumped FWM, one beam from either upper or lower any one output from CMZI-1 and the other beam from any one output of CMZI-2 are inserted within the SOA **S-1, S-2, S-3** and **S-4.** A very low band pass filter centered at frequency $2\omega_1-\omega_2$ is placed after each SOA to pass a proper FWM idler light component having the same frequency with its corresponding phase $2\phi_1-\phi_2$. For self pumped FWM in each of these four SOA is connected with any of the two outputs of the CMZI-1 and 2 are given in the table-3.

phases ($\Phi_{p1}$, $\Phi_{p2}$). The implementation of the NOR logic by phase difference is shown in the table-4 and the construction in figure-3.
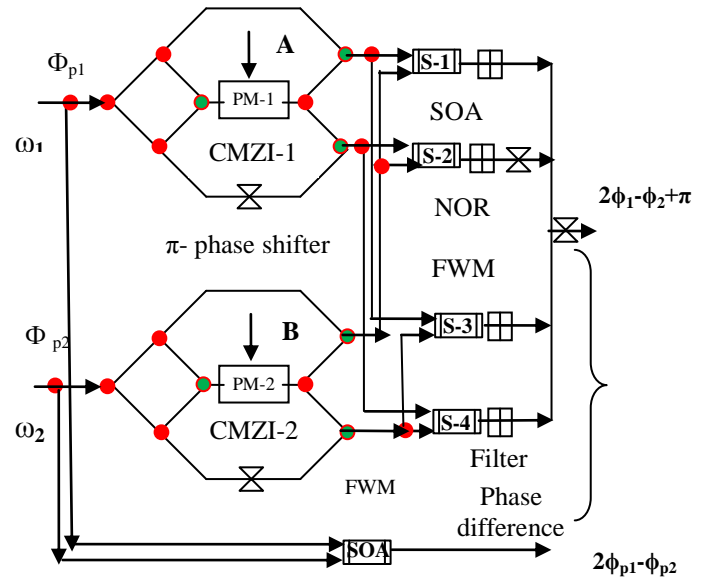


Fig.3.Proposed scheme of optical NOR logic gate.

TABLE 4

Realization of the NOR logic through phase difference.

| A | B | Phase of the Light Wave from CMZI-1 & CMZI-2 $\Phi_1$ & $\Phi_2$ | Acting SOA for FWM in the simultaneous presence of the two pump waves with $\omega_1, \omega_2$ | Phase of the final output wave after introduction of phase by $\pi$ phase shifter $2\phi_1-\phi_2+\pi$ | Phase difference = $2\phi_1-\phi_2+\pi-(2\phi_{p1}-\phi_{p2})$ | Y Output |
|---|---|---|---|---|---|---|
| 0 | 0 | $\Phi_{p1}$ $\Phi_{p2}$ | S-1 | $2\Phi_{p1}-\Phi_{p2}+\pi$ | $\pi$ | 1 |
| 1 | 0 | $\Phi_{p1}+\pi$ $\Phi_{p2}$ | S-2 ( extra $\underline{\pi}$ phase) | $2\Phi_{p1}-\Phi_{p2}+2\pi+\pi+\underline{\pi}$ | $4\pi$ | 0 |
| 0 | 1 | $\Phi_{p1}$ $\Phi_{p2}+\pi$ | S-3 | $2\Phi_{p1}-\Phi_{p2}-\pi+\pi$ | 0 | 0 |
| 1 | 1 | $\Phi_{p1}+\pi$ $\Phi_{p1}+\pi$ | S-4 | $2\Phi_{p1}-\Phi_{p2}+\pi+\pi$ | $2\pi$ | 0 |

TABLE 3

THE OUTPUTS WITH PHASE CONNECTED WITH THE FOUR SOAS

| For FWM in SOA | The output injected inside SOA from CMZI-1 with phase $\Phi_1$ | The output injected inside SOA from CMZI-2 with phase $\Phi_2$ |
|---|---|---|
| **S-1** | Upper output-$\Phi_{p1}$ | Upper output-$\Phi_{p2}$ |
| **S-2** | Lower output-$\Phi_{p1}+\pi$ | Upper output-$\Phi_{p2}$ |
| **S-3** | Upper output-$\Phi_{p1}$ | Lower output-$\Phi_{p2}+\pi$ |
| **S-4** | Lower output-$\Phi_{p1}+\pi$ | Lower output-$\Phi_{p2}+\pi$ |

Therefore always in each binary combination of the inputs A and B, only one SOA will produce FWM output due to simultaneous presence of the two pump waves with frequencies $\omega_1, \omega_2$ from any outputs of CMZI-1 and CMZI-2. Here in this scheme to implement the logic gates, the outputs of all these four SOAs are combined in a single light wave. But a $\pi$ phase sifter is inserted over the FWM output of SOA S-2 before combining with the others. For logic realization again a $\pi$ phase shifter is placed over the final combined light wave. The NOR logic is realized by the phase difference in between this final wave with the idler component of same frequency is produced by FWM in same type of SOA using these same two light pump waves with only the same initial

In this scheme all optical NOR logic gate is based on phase encoding with the help of non-degenerate self pumped FWM in SOA. Therefore the high spectral efficiency with fibre nonlinearity tolerance property of phase encoding procedure and the swiftly occurring self pumped FWM process makes

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this scheme very much sensible for forthcoming computing techniques.The prefixed input phase in case of simple binary phase encoding system cannot be preserved properly due to nonlinearity of the fibre. But in this proposal a different type of phase encoding procedure has been used by taking the phase difference value of the light waves. Phase synchronization must be necessary for proper implementation of this scheme. Optical delay with proper length of fibre can be used in this purpose. To maintain polarisation of the pump waves for efficient FWM in SOA, polarisation controller can be utilized over them. Any logic can be realized from the same scheme just by some changes in the placement of $\pi$ phase shifter over the fibre. In this proposed arrangement of CMZI with SOA can be employed also for the simultaneous realization of the number of logic gates

## *Acknowledgment*

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