

## Method of implementing frequency-encoded NOT, OR and NOR logic operations using lithium niobate waveguide and reflecting semiconductor optical amplifiers

SISIR KUMAR GARAI<sup>1,\*</sup> and SOURANGSHU MUKHOPADHYAY<sup>2</sup>

<sup>1</sup>Department of Physics, M.U.C. Women's College, Burdwan 713 104, India

<sup>2</sup>Department of Physics, The University of Burdwan, Burdwan 713 104, India

\*Corresponding author

E-mail: sisir\_garai@yahoo.co.in; sourangshu2004@gmail.com

MS received 23 October 2008; accepted 22 June 2009

**Abstract.** Optics has already proved its strong potentiality for the conduction of parallel logic, arithmetic and algebraic operations. In the last few decades several all-optical data processors were proposed. To implement these processors different data encoding/decoding techniques have been reported. In this context, polarization encoding technique, intensity-based encoding technique, tristate and quaternary logic operation, multivalued logic operations, symbolic substitution techniques etc. may be mentioned. Very recently, frequency encoding/decoding technique has drawn interest from the scientific community. Frequency is the fundamental character of any signal; and it remains unaltered in reflection, refraction, absorption etc. during the propagation and transmission of the signal. This is the most important advantage of frequency encoding technique over the conventional encoding techniques. In this communication the authors propose a new scheme for implementing NOT, OR and NOR logic operations. For this purpose co-propagating beams having different frequencies in C-band (1535–1560 nm) have been used for generating cascaded sum and difference frequency, exploiting the nonlinear response character of periodically poled LiNbO<sub>3</sub> waveguide. The cross-gain modulation property of the semiconductor optical amplifier (SOA) and the wavelength conversion property of the reflecting semiconductor optical amplifiers (RSOA) are exploited here to implement the desired optical logic and arithmetic operations.

**Keywords.** Nonlinear optics; sum and difference frequency generation; optical filter; LiNbO<sub>3</sub> crystal; semiconductor optical amplifier; optical logic gates; add and drop multiplexer.

**PACS Nos** 42.79.Ta; 42.79.Nv; 42.70.Nq; 42.79.Mp

### 1. Introduction

Optics has shown its strong and potential role in information processing, computation, data and image processing because of its inherent parallelism. Several

all-optical data processors, as well as image processors have been proposed with both conceptual and practical realizations [1–5]. Those processors established the strong role of optics in overcoming the speed limitation in electronic processors.

In Boolean logic-based implementation of gates, the states of information are generally established by the presence (1) and absence (0) of the signals. Several problems are to be faced if optics is directly used to implement the Boolean logic gates with the coding norm, as the presence of optical signal is 1 and absence of optical signal is 0. For these, many alternative approaches are reported to encode 1 and 0 with optical signal. In some cases, by the exploitation of spatial input encoding/decoding technique, space-variant logic operations, symbolic logic substitution method, theta ( $\theta$ ) modulation scheme and many other several optical processors were seen to be implemented. It is also seen that many proposals are reported where the same coding mechanism (i.e. presence of optical signal is regarded as 1 and absence as 0) is followed to implement the optical logic gates in Boolean mechanism. In those cases a prefixed intensity level is highly preferred to encode the logic bit '1'. Fall of the intensity level due to absorption at different points in the logic circuits changes the prefixed value of logic 1 state. In most of the cases the all-optical logic gates are implemented by nonlinear materials extending its second-order nonlinearity. These materials guide the light to pass through different channels if the intensity of light varies. So the change of this prefixed value of intensity creates some major problems in channel selection and therefore this intensity-based encoding principle is not at all a trouble-free one. Similarly, polarization encoding principle is also a widely reported mechanism. Here two orthogonal polarized states of light are represented by 1 and 0 logic states respectively. This also produces several problems in implementation of the gates of the logic families, as the state of polarization may alter at reflecting and refracting points during transmission and propagation. Similarly, other coding norms may extend some other limitations in wide-range data processing.

We can mention also the polarization encoding technique for implementing some optical processors [6–8]. Polarization encoding technique has some basic advantages and therefore it can be successfully used to code optical bits 1 and 0 (in Boolean system) and 1, 0,  $\bar{1}$  (in tristate system). Different arithmetic operations can be implemented optically by polarization encoding technique. In spite of all the advantages, all of the above coding norms and techniques extend the loss-dependent problem as mentioned above.

In contrast to those proposals one can mention a frequency-encoded technique as an advantageous one to implement Boolean logic [8]. It is known that if 1 and 0 logic states are encoded by two different frequencies then one can be sure about the state of a signal during transmission. That is, if 1 state is encoded by the frequency  $\nu_1$  and the 0 state by  $\nu_2$  then  $\nu_1$  and  $\nu_2$  will remain unaltered throughout the transmission of data, even if it suffers from reflection, attenuation loss, refraction etc. We know that NOT and OR operations are the most fundamental ones in logic family and NOR logic gate is a universal logic gate. In this communication the authors propose a new concept of implementing NOT, OR and NOR logic operations by frequency encoding technique. To develop these, one can use the sum frequency generation (SFG) and difference frequency generation (DFG) techniques, exploiting the cascaded second-order nonlinearity in periodically poled LiNbO<sub>3</sub> waveguide and

wavelength conversion property of semiconductor optical amplifier. The attractive advantages of periodically poled LiNbO<sub>3</sub> waveguide are that it exhibits ultrafast response, free from spontaneous emission of noise and no intrinsic frequency chirp arises [9–16]. Semiconductor optical amplifier (SOA) and reflective semiconductor optical amplifier (RSOA) exhibit efficient cross-gain modulation (XGM) and wavelength conversion property which are independent of polarization, insensitive to the wavelength of the input data, provided it is within its gain bandwidth [17–22]. The XGM and wavelength conversion properties are controlled by the intensity of the pump beam.

## **2. Principle of frequency-encoded different logic operations**

The process of frequency-encoded different logic operations are based on three basic principles as mentioned below.

- (i) The principle of cascaded sum and difference frequency generation by means of three co-propagating signals having different frequencies in C-band in a nonlinear periodically poled LiNbO<sub>3</sub> waveguide.
- (ii) Principle of frequency routing by means of optically add/drop multiplexers by proper tuning.
- (iii) The principle of conversion of a frequency to another appropriate frequency exploiting the cross-gain modulation property of SOAs and RSOAs.

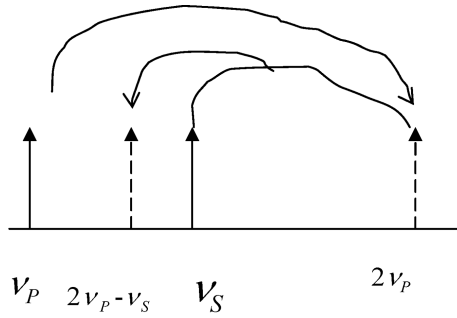
### *2.1 The principle of cascaded sum and difference frequency generation*

According to the first principle, two pump laser beams of frequencies  $\nu_1$  and  $\nu_2$  having sufficient energy and propagating through a nonlinear optical material having first-order nonlinearity will generate a signal of sum frequency ( $\nu_1 + \nu_2$ ).

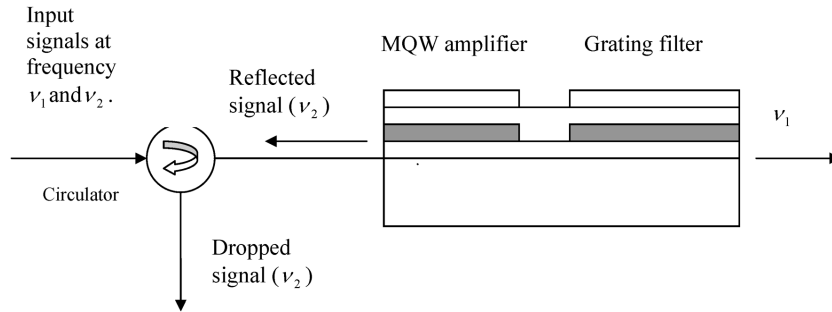
When the beam of frequency ( $\nu_1 + \nu_2$ ) is coupled with a weak signal of frequency  $\nu_S$  with energy ratio 90 : 10 and then passed through a waveguide made of periodically poled LiNbO<sub>3</sub> waveguide (PPLN) with proper quasi-phase matching then the sum frequency ( $\nu_1 + \nu_2$ ) beam by interaction with the co-propagating signal beam of frequency  $\nu_S$  ( $\chi^{(2)} : \chi^{(2)}$  interaction) generates the converted signal frequency  $\nu_c = \nu_1 + \nu_2 - \nu_S$ . Thus the output beam will be consisting of beams having frequencies  $\nu_1$ ,  $\nu_2$ , ( $\nu_1 + \nu_2$ ),  $\nu_c (= \nu_1 + \nu_2 - \nu_S)$  and  $\nu_S$  as shown in figure 1 [10,14–16]. Now if the frequency of the two pumps is the same, i.e.  $\nu_1 = \nu_2 = \nu_P$  (say), then output frequency becomes  $2\nu_P - \nu_S$ .

### *2.2 Principle of frequency routing*

In a specific channel the optical signals may be of different frequencies. These data signals of different frequencies can be directed through separate paths using ODM (optical add/drop multiplexer) [11,12,19]. The function of the wavelength ODM is to separate a particular wavelength channel without interference from



**Figure 1.** Cascaded sum and difference frequency generation by PPLN waveguide.

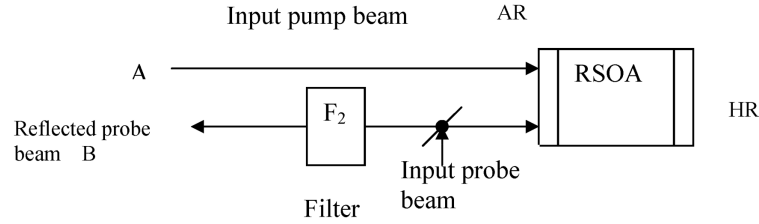


**Figure 2.** Scheme of frequency routing by ADMs.

adjacent channels. This can be achieved by using an integrated SOA with a grating filter as shown in figure 2. The filter can be tuned at different frequencies by changing the bias current of SOA. The selected wavelength channel is reflected by the filter, amplified a second time by the multiquantum well (MQW) section and extracted to a drop port by means of a circulator. The remaining channel passes through the filter section without any drop. In figure 2 the input signal consists of frequencies  $\nu_1$  and  $\nu_2$ .  $\nu_2$  is dropped from the incoming data signal of frequencies  $\nu_1$  and  $\nu_2$  by suitably tuning the ADM for the reflecting frequency  $\nu_2$ . In the same way different frequencies can be routed to different channels using optical ADM. In this connection we can mention the work entitled ‘Tunability of polarization – insensitive wavelength converters based on four-wave mixing in semiconductor optical amplifiers’ by Lacey *et al* and the references used in this paper [21].

### 2.3 The principle of frequency conversion by RSOA

The principle of frequency-encoded inversion operation using RSOA is based on all-optical wavelength conversion exploiting the XGM character of RSOA [17,18,22]. The material gain spectrum of an SOA is homogeneously broadened. This means that change in carrier density of this amplifier affects all the input signals. So it is possible for a strong signal at one wavelength to affect the gain of a weak signal



**Figure 3.** Scheme of frequency conversion by RSOA.

at another wavelength. This nonlinear mechanism is XGM. In this approach, an intensity-modulated signal at frequency  $\nu_1$ , referred to as pump beam, propagates through a RSOA. Its intensity is high enough so that it can compress the gain of the RSOA significantly. The induced gain variations are impressed upon a second input to the RSOA, a CW beam at different frequency  $\nu_2$ , called the probe beam. In this case the wavelength-converted data is the complementary copy of the original data. The scheme of principle operation is shown in figure 3. HR and AR are the highly reflecting and antireflecting coating on RSOA, A is the input terminal of the pump beam at frequency  $\nu_1$ , F<sub>2</sub> is the optical filter tuned at the pass frequency of  $\nu_2$  and B gives the wavelength-converted output at frequency  $\nu_2$  at the expense of input signal of frequency  $\nu_1$ . If one wants to convert a signal of frequency  $\nu_1$  to another frequency  $\nu_3$  (say) within the same gain bandwidth he has to select the probe beam at frequency  $\nu_3$  and the output of the converted probe beam should be passed through the filter having pass frequency  $\nu_3$ . By this mechanism a signal of one frequency can be converted to another of the desired frequency in C-band.

### 3. The operational scheme of inversion operation

It is widely known that the inversion operation is the most fundamental operation in the logic world. In Boolean logic it is seen that inversion logic promotes 0 state when its input is in 1 state and it enhances 1 state if the input is in 0 state. This inversion operation has been successfully implemented by exploiting the second harmonic generation and wave mixing techniques [8]. For this purpose the frequency  $2\nu$  was encoded as 1 state and frequency  $\nu$  as 0 state. To execute the scheme,  $2\nu$  frequency was recovered from  $\nu$  by second harmonic generation technique in nonlinear material. 0 state was recovered from 1 state, i.e.  $\nu$  frequency was obtained from  $2\nu$  frequency by frequency subtraction method using proper phase matching conditions. Here, in our new proposed scheme, we encode two different frequencies  $\nu_1$  and  $\nu_2$  of two beams in C-band (other than  $\nu$  and  $2\nu$ ) as the input data beams.

Realization of the proposed frequency-encoded NOT operations is based on (i) the principle of cascaded sum and difference frequency generation, (ii) principle of frequency routing and (iii) principle of wavelength conversion. The scheme of the experimental set-up for implementing inversion operation is shown in figure 4 and the truth table is given in table 1.

Table 1.

Input $A$	$Y = \bar{A}$
$\nu_1(0)$	$\nu_2(1)$
$\nu_2(1)$	$\nu_1(0)$

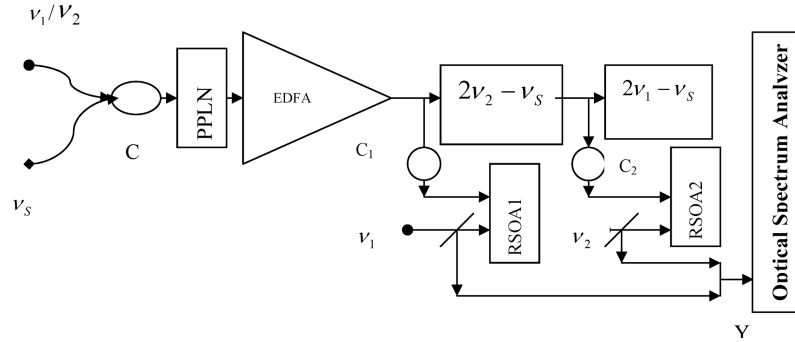


Figure 4. Scheme of inversion operation.

In our proposed scheme of operation we have selected  $\nu_1$  and  $\nu_2$  as the possible different input signal frequencies. Further, we have encoded/decoded the signal of frequency  $\nu_1$  as 0 state and the signal of frequency  $\nu_2$  as 1 state. In our scheme the inversion operation is said to be implemented if the input signal beam of frequency  $\nu_1$  can be converted into beam of frequency  $\nu_2$  and vice versa.

When a stronger input beam of frequency  $\nu$  is coupled with a signal of frequency  $\nu_s$  in 90:10 ratio by means of a coupler (C) and then injected through the periodically poled LiNbO<sub>3</sub> waveguide, then the pump beam first converted into its second harmonic ( $2\nu$ ) and then with the interaction of signal beam via  $\chi^2:\chi^2$  nonlinear process, a converted signal of frequency ( $2\nu - \nu_s$ ) is generated. If the input pump beam is of frequency  $\nu_1$ , then the converted output is of frequency ( $2\nu_1 - \nu_s$ ) and for the input pump beam of frequency  $\nu_2$ , the frequency of the converted beam is ( $2\nu_2 - \nu_s$ ).

The converted beam is now passed successively through optical add/drop multiplexers (ADMs). The first ADM is biased with such a current that it can reflect only the ( $2\nu_2 - \nu_s$ ) and then it is dropped down by means of a circulator ( $C_1$ ). The second ADM is biased for reflecting frequency ( $2\nu_1 - \nu_s$ ) and the reflected beam of this frequency is dropped down by means of circulator  $C_2$ . The beam of frequency ( $2\nu_2 - \nu_s$ ) circulated through  $C_1$  is injecting as the pump beam for the RSOA1. Here the probe beam is a weak signal of frequency  $\nu_1$  and the amplified probe beam of RSOA1 is passed through the optical filter of pass frequency  $\nu_1$  and finally it is connected to the output end (Y). Similarly, the beam of frequency ( $2\nu_1 - \nu_s$ ) obtaining from circulator  $C_2$  is serving as the pump beam for RSOA2. A weak signal of frequency  $\nu_2$  is applied in RSOA2 as the probe beam and the output of the amplified probe beam is passed through the optical filter ( $F_2$ ) of pass frequency  $\nu_2$  and then it is connected to the output terminal (Y). Now we explain the inversion operation for two input beams of frequencies  $\nu_1$

(wavelength  $\lambda_1 = 1543$  nm) and  $\nu_2$  (wavelength  $\lambda_2 = 1555$  nm) and the signal beam of frequency  $\nu_S$  ( $\lambda_S = 1536$  nm).

*Case 1. When input probe beam is of frequency  $\nu_1$  (0 state).* Here the probe beam with the interaction of signal beam in PPLN waveguide will generate a converted beam of frequency  $(2\nu_1 - \nu_S)$  (1536 nm). The converted beam will then pass through ADM1 as it is tuned for reflection only at frequency  $(2\nu_2 - \nu_S)$  (1560 nm). The transmitted beam through ADM1 will now be reflected by ADM2 (tuned for reflection at wavelength 1539 nm) and drop to the circulator port ( $C_2$ ). This beam (1536 nm) will now behave as the pump beam for RSOA2 and it will transfer its energy to the probe beam of frequency  $\nu_2$  (1555 nm) by XGM process and finally give the beam of frequency  $\nu_2$  at the output end after passing through the filter  $F_2$ . Therefore, we will obtain a signal of frequency  $\nu_2$  (1555 nm) (1 state) at the output end due to an input signal of frequency  $\nu_1$  (0 state) (1543 nm) at the input end.

*Case 2. When input probe beam is of frequency  $\nu_2$  (1 state).* Here the probe beam with the interaction of signal beam in PPLN will generate a converted beam of frequency  $(2\nu_2 - \nu_S)$ . The converted beam will be reflected by ADM1 as it is biased for reflection at frequency  $(2\nu_2 - \nu_S)$  and drop to the circulator port ( $C_1$ ). The transmitted beam through  $C_1$  will now serve as the pump beam for RSOA1 and it will transfer its energy to the probe beam of frequency  $\nu_1$  by XGM process and finally give the beam of frequency  $\nu_1$  at the output end after passing through the filter  $F_1$ . Therefore, it is possible to get a signal of frequency  $\nu_1$  (0 state) (1543 nm) at the output end at the expense of input signal of frequency  $\nu_2$  (1 state) (1555 nm) at the input end.

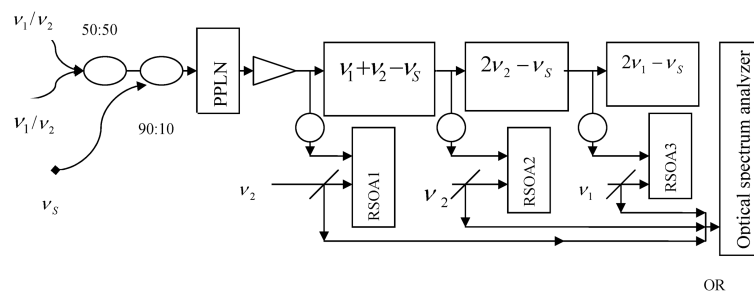
Combining Cases 1 and 2 we see that it is possible to get a signal of frequency  $\nu_1$  (0 state) at the output end at the expense of input signal of frequency  $\nu_2$  (1 state) at the input end and a signal of frequency  $\nu_2$  (1 state) at the output end due to an input signal of frequency  $\nu_1$  (0 state) at the input end. Thus the above-mentioned scheme suggests the implementation of frequency-encoded inversion operation. The operation can be summarized as

$$\begin{aligned} \nu_1 \text{ (0 state) } (\lambda_1 = 1543 \text{ nm}) &\rightarrow (2\nu_1 - \nu_S) \text{ (1536 nm)} \\ &\rightarrow \nu_2 \text{ (1 state) (1555 nm),} \\ \nu_2 \text{ (1 state) (1555 nm)} &\rightarrow (2\nu_2 - \nu_S) \text{ (1560 nm)} \\ &\rightarrow \nu_1 \text{ (0 state) } (\lambda_1 = 1543 \text{ nm}). \end{aligned}$$

#### 4. The operational scheme of OR logic operation

Realization of frequency-encoded OR logic operations are also based on (i) the principle of cascaded sum and difference frequency generation, (ii) principle of frequency routing and (iii) principle of wavelength conversion. The scheme of the experimental set-up for implementing inversion operation is shown in figure 5.

Here two input beams A and B of power 10–11 dB, having different possible frequencies  $\nu_1$  and  $\nu_2$  are mixed in the ratio 50:50 by means of a coupler and then these beams are mixed with a signal of frequency ( $\nu_S$ ) by means of a second coupler



**Figure 5.** Scheme of OR logic operation.

in 90:10 ratio. This mixture is then passed through the periodically poled LiNbO<sub>3</sub> waveguide. Here two input beams will first generate the sum frequency ( $\nu_1 + \nu_2$ ) due to  $\chi^2$ -type of interaction within PPLN waveguide and then with the interaction of signal beam it generates the difference frequency ( $\nu_1 + \nu_2 - \nu_S$ ). The values of  $\nu_1$  (1543 nm),  $\nu_2$  (1555 nm) and  $\nu_S$  (1550 nm) are so chosen in the C-band that  $(2\nu_1 - \nu_S)$  (1536 nm),  $(2\nu_2 - \nu_S)$  (1560 nm) and  $(\nu_1 + \nu_2 - \nu_S)$  (1548 nm) also remain in the C-band. If the length of the PPLN is small then some unconverted pump beam frequencies as well as the frequency of the signal beam may be present at the output end of the PPLN. But if the length of PPLN is greater than 6 cm, the possibility of the existence of the unconverted input beam frequencies as well as the frequency of the signal beam will be absent.

Depending on different possible sets of input beam frequencies the converted frequencies at the output end of the PPLN waveguide are  $(2\nu_1 - \nu_S)$ ,  $(2\nu_2 - \nu_S)$ ,  $(\nu_1 + \nu_2 - \nu_S)$  in addition to the frequencies of unconverted input beam and the signal beam. The power of the converted signal is very low ( $\approx -30$  dB) [10,12].

To obtain the desired OR logic operation, the output of PPLN waveguide is first amplified by means of SOA/EDFA to a level 4 dB to 8 dB and then allowed to pass through three successive ADMs which are tuned at different reflecting frequencies. The reflecting beam from each ADM is dropped out by means of circulator. Each dropped beam is injecting as the pump beam for RSOA in the next stage. Here by XMG process the pump beam transfers its energy to the probe beam of its respective RSOA via frequency conversion (up- or down-) process. Outputs of all RSOAs are coupled together to get the result of OR logic operation. Here ADM1 is tuned at the reflecting frequency ( $\nu_1 + \nu_2 - \nu_S$ ) by changing the bias current of the SOA (part of ADM). Similarly, ADM2 is tuned at the reflecting frequency ( $2\nu_2 - \nu_S$ ), and ADM3 at the reflecting frequency ( $2\nu_1 - \nu_S$ ). The reflected beam from ADM1 is circulated to drop port by means of a circulator. The drop beam of frequency ( $\nu_1 + \nu_2 - \nu_S$ ) is then connected to RSOA1 where it is serving as the pump beam. A weak beam of frequency  $\nu_2$  is supplied externally as the probe beam for RSOA1. Here the pump beam of frequency ( $\nu_1 + \nu_2 - \nu_S$ ) will transfer its energy to the probe beam of frequency  $\nu_2$  by XGM process. The output of the RSOA1 obtaining from probe end is passed through an optical filter with pass frequency  $\nu_2$  to get the final output. Here frequency  $\nu_2$  is obtained at the output end of RSOA1 at the cost of pump beam of frequency ( $\nu_1 + \nu_2 - \nu_S$ ).



Similarly, the drop beam of frequency  $(2\nu_2 - \nu_S)$  from ADSM2 is acting as the pump beam of RSOA2 which transfers its energy to the probe beam of frequency  $\nu_2$  by XGM. The drop beam of frequency  $(2\nu_1 - \nu_S)$ , from ADM3 is acting as the pump beam of RSOA3 which transfers its energy to the probe beam of frequency  $\nu_1$  by XGM. The output of all three RSOAs are coupled together to get the output of frequency-encoded OR logic operation. Now we explain the operation of OR logic for four different possible sets of input beam (A and B) frequencies having the fixed signal frequency  $\nu_S$ .

*Set I. When both input beam A and input beam B are of frequency  $\nu_1$ .* Then the converted signal of frequency  $(2\nu_1 - \nu_S)$  obtaining from PPLN waveguide will pass through ADM1 and ADM2 but will be reflected back by ADM3 and reach RSOA3 where it will behave as pump beam. Here it will transfer its power to the probe beam of frequency  $\nu_1$  by XGM process. Therefore, frequency  $\nu_1$  is obtained at the output end when both input beam A and input beam B are of frequency  $\nu_1$ .

*Set II. When input beam A is of frequency  $\nu_1$  and input beam B is of frequency  $\nu_2$ .* Here the converted signal is of frequency  $(\nu_1 + \nu_2 - \nu_S)$  at the output end of PPLN waveguide. After emerging from PPLN waveguide it will be reflected back by ADM1 as it is tuned for reflection at that frequency and reach RSOA1 where it will act as pump beam. Here, it will transfer its power to the probe beam of frequency  $\nu_2$  by XGM process. Therefore, frequency  $\nu_2$  is obtained at the output end when input beam A is of frequency  $\nu_1$  and input beam B is of frequency  $\nu_2$ .

*Set III. When input beam A is of frequency  $\nu_2$  and input beam B is of frequency  $\nu_1$ .* Here the converted signal is of frequency  $(\nu_1 + \nu_2 - \nu_S)$  at the output end of PPLN waveguide. Here the situation is identical to the Set II. Therefore, frequency  $\nu_2$  is obtained at the output end when input beam A is of frequency  $\nu_2$  and input beam B is of frequency  $\nu_1$ .

*Set IV. When both the input beams A and B are of frequency  $\nu_2$ .* Then the converted signal at the end of PPLN is a signal of frequency  $(2\nu_2 - \nu_S)$ . This output signal of PPLN waveguide will pass through ADM1 but will be reflected back by ADM2 as it is tuned for reflection at frequency  $(2\nu_2 - \nu_S)$ , and after reflection reach RSOA2 via a circulator where it will play the role of the pump beam. Here it will transfer its energy to the probe beam of frequency  $\nu_2$  by nonlinear interaction. Therefore, frequency  $\nu_2$  is obtained at the output end when both input beams A and B are of frequency  $\nu_2$ .

Thus the output results for the above four different sets of frequency-encoded input beams satisfy the frequency-encoded truth table of OR logic operation as shown in table 2.

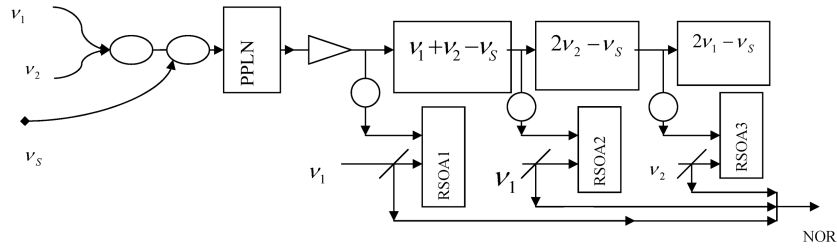
## 5. The operational scheme of NOR logic operation

The experimental set-up of the frequency-encoded NOR logic operation is shown in figure 6 and the truth table of it is shown in table 3.

Here ADM1 is tuned at reflection frequency  $(\nu_1 + \nu_2 - \nu_S)$ , ADM2 is for  $(2\nu_2 - \nu_S)$  and ADM3 is for frequency  $(2\nu_2 - \nu_S)$ . The reflected beam from ADM1 is injected

**Table 2.**

$A$	$B$	$Y = A + B$
$\nu_1(0)$	$\nu_1(0)$	$\nu_1(0)$
$\nu_1(0)$	$\nu_2(1)$	$\nu_2(1)$
$\nu_2(1)$	$\nu_1(0)$	$\nu_2(1)$
$\nu_2(1)$	$\nu_2(1)$	$\nu_2(1)$



**Figure 6.** Scheme of NOR logic operation.

**Table 3.**

$A$	$B$	$Y = \bar{A} \cdot \bar{B}$
$\nu_1(0)$	$\nu_1(0)$	$\nu_2(1)$
$\nu_1(0)$	$\nu_2(1)$	$\nu_1(0)$
$\nu_2(1)$	$\nu_1(0)$	$\nu_1(0)$
$\nu_2(1)$	$\nu_2(1)$	$\nu_1(0)$

as the pump beam for RSOA1 where it will transfer its energy to the probe beam of frequency  $\nu_1$ . Thus, it is possible to get the frequency  $\nu_1$  as output beam at the cost of frequencies  $\nu_1$  and  $\nu_2$  at the input end.

ADM2 is tuned for frequency  $(2\nu_2 - \nu_s)$ . Therefore, when both the input beams are of frequencies  $\nu_2$  then the converted beam of frequency  $(2\nu_2 - \nu_s)$  will reflect back and serve as the pump beam for RSOA2. Here this beam will be converted to a beam of frequency  $\nu_1$  by the XGM property of SOA. Therefore, at the output end of the probe beam, it is possible to get a beam of frequency  $\nu_1$  due to both the input beams of frequencies  $\nu_2$ .

When both the input beams are of frequencies  $\nu_1$ , then the converted signal of frequency  $(2\nu_1 - \nu_s)$  will reflect from ADM3 and behave as the pump beam for RSOA3 where it will be converted to a beam of frequency  $\nu_2$ . The output end of the probe beam of frequency  $\nu_1$  will be obtained for input beams both having frequencies  $\nu_2$ .

Thus we see that the output of the above-mentioned scheme for different possible combinations of input beams is the same as that of a frequency-encoded NOR logic operation as given in table 3.

**6. Conclusion**

The whole operation is all-optical and one can expect a THz operation speed from the system. This method can be extended to implement many other logic operations like flip-flop, multiplexer, demultiplexer etc. and we believe that these will be included in our future communications. The potential advantage of these logic gates over many other established ones is the frequency-dependent input/output encoding, for which the coded information (1 or 0) in a signal remains unaltered in reflection, refraction, transmission, absorption etc. It is seen that in different nonlinear material-based logic operations, the intensity of the optical signal against bit value 1 is to be maintained constant. This is an essential requirement for the all-optical operation. The strong disadvantage of such nonlinear material-based logic operation is that any fluctuation of intensity creates a change of direction of the outcoming rays from a nonlinear material, which can damage the total system. Therefore, the constancy of the prefixed intensity level is highly desired there. Here, in our proposed scheme of implementation of logic operation by frequency encoding mechanism, it is irrelevant whether any intensity fluctuation, loss of light etc. arise. Therefore, this proposed scheme does not only give a high speed operation, but also offers a trouble-free and noise-free system. The most advantageous aspect of this scheme is that the same device can be used to implement different logic operations only by changing the frequency of reflection of ADMs by changing the biasing current of SOA, integrated part of an ADM.

All the operations proposed here are based on the nonlinear response character of periodically poled LiNbO<sub>3</sub> waveguide and wavelength conversion and optical add-drop multiplexing properties of RSOAs and SOAs. The sum and difference frequency generation by PPLN is an ultrahigh speed process with a wide operational bandwidth of about 50 nm for the 6 cm long PPLN waveguide. Moreover, the PPLN waveguide is almost free from noise due to spontaneous emission. Both up-conversion and down-conversion of frequencies are realized by RSOA. However, the extinction ratio (ER) is always better for down-conversion compared to up-conversion. Wavelength conversion using RSOA is superior to conversational SOA because RSOA can operate with low power level [22]. Its wide gain band provides the feasibility of wavelength conversion over a wide range. Power of the probe beam is kept in the range  $-4$  dBm to  $-2$  dBm for RSOAs and for conversational SOA it is maintained at  $-2$  dBm, whereas the power of the pump beam is maintained in the range  $4$ – $10$  dBm. The efficiency of the cascaded sum and difference frequency signals are low. Larger the difference of the input beam frequencies ( $\nu_1 - \nu_2$ ) for a given value of signal frequency ( $\nu_S$ ), better will be the conversion efficiency in the C-band. Therefore, here ( $\nu_1 - \nu_2$ ) is kept at  $12$  nm. To use these beams as pump beams for the next stages, energies of these signals are to be amplified properly ( $4$  dB– $10$  dB). For this purpose EDFAs/SOAs may be used. It is to be remembered that power level of the probe beams of RSOAs does not fall below  $-8$  dBm so that wavelength conversion by RSOAs can exhibit a good performance. All the frequencies [ $\nu_1$  ( $1542$  nm),  $\nu_2$  ( $1548$  nm),  $\nu_S$  ( $1545$  nm),  $(2\nu_1 - \nu_S)$  ( $1539$  nm),  $(2\nu_2 - \nu_S)$  ( $1551$  nm) and  $(\nu_1 + \nu_2 - \nu_S)$  ( $1545$  nm)] of this scheme fall in the range of C-band. This makes the scheme attractive for the use in optical networks as the variation of the gain with polarization of the input signal (polarization-dependent

gain (PDG)) is very low ( $< 1$  dB) across C-band. Here it is needless to control the state of polarization of the input beams.

## References

- [1] S Mukhopadhyay, *Opt. Comm. (The Netherlands)* **76(5–6)**, 309 (1990)
- [2] S Dhar and S Mukhopadhyay, *Opt. Engng (USA)* **45(11)**, 115201-1 to 115201-4 (2006)
- [3] S Mukhopadhyay, D N Das and N Pahari, *Appl. Opt. (USA)* **43(33)**, 6147 (2004)
- [4] S Mukhopadhyay, *Appl. Opt. (USA)* **31**, 4622 (1992)
- [5] K Roychowdhury, P P Das and S Mukhopadhyay, *Opt. Engng (USA)* **44(3)**, 035201-1 to 035201-5 (2005)
- [6] W Wu, S Campbell, S Zhou and P Yeh, *Opt. Lett.* **18(20)**, 1742 (1993)
- [7] M Martinelli, P Martelli and S M Pietralunga, *J. Lightwave Technol.* **24**, 4172 (2006)
- [8] S K Garai, D Samanta and S Mukhopadhyay, *Opt. Optoelectron. Technol. China* **6(4)**, 43 (2008)
- [9] K Gallo, G Assanto and G Stegeman, *Appl. Phys. Lett.* **7**, 1021 (1997)
- [10] Jian Wang, Junqia NG Sun, Chauanhong Luo and Qizhen Sun, *Opt. Express* **13(19)**, 7405 (2005)
- [11] S Yu W Gu, *IEEE J. Quantum Electron.* **41**, 1007 (2005)
- [12] Saurabh Kumar and Alan E Willner, *Opt. Express* **14(22)**, 10255 (2006)
- [13] M H Chou, I Brener, M M Fejer, E E Chaban and S B Christman, *IEEE Photon Technol. Lett.* **11**, 653 (1999)
- [14] Wenjie Lu *et al*, *Opt. Express* **16(1)**, 355 (2008)
- [15] J Sun, W Liu, J Tian, J R Kurz and M M Fejer, *IEEE Photon. Technol. Lett.* **15**, 1743 (2005)
- [16] Jun-feng Zhang, Yuping Chen, Feng Lu and Xianfeng Chen, *Opt. Express* **16(10)**, 6957 (2008)
- [17] M Asghari, I H White and R V Penty, *J. Lightwave Technol.* **15(17)**, 1181 (1997)
- [18] H Soto, D Erasme and G Guekos, *IEEE Photon. Technol. Lett.* **11**, 970 (1999)
- [19] L Q Guo and M J Connelly, *J. Lightwave Technol.* **23(12)**, 4037 (2005)
- [20] L Q Guo and M J Connelly, *Opt. Express* **14(7)**, 2938 (2006)
- [21] J P R Lacey, M A Summerfield and S J Madden, *J. Lightwave Technol.* **16(12)**, 2419 (1998)
- [22] L Q Guo and M J Connelly, *Opt. Commun.* **281(17)**, 4470 (2008); doi: 10.1016/j.optcom.2008.04.054