



Alternative approach of developing frequency encoded BCD encoder and decoder with polarisation switches

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Abstract Present day's communication technology demands high data processing speed, potential band width with enormous data handling capacities, and this can be achieved with light wave technology. All optical encoder and decoder have paramount importance in data communication network. In this article, the authors have proposed a method of developing an optical encoder and a decoder circuit that has been working exploiting the nonlinear polarisation switching action of semiconductor optical amplifier. Frequency encoded data have attributed an extra dimension of the proposed scheme. Use of frequency encoded data in C-band, very fast polarisation switching action of SOA, frequency independent gain of the SOA in C-band and the use of optical MUX and DEMUX make the proposed scheme secure and highly effective in WDM communication network which the backbone of the present day's communication network. Simulated results enhance the acceptability of the proposed scheme.

Keywords Semiconductor optical amplifier (SOA) · Cross-polarisation gain · Optical encoder · Optical decoder · Optical multiplexer (MUX) and demultiplexers (DMUX)

Introduction

In digital data-based communication technology, encoding and decoding of data is of paramount importance for secure communication. In digital system, a set of ten switches, one for each numeral between 0 and 9, is one of the most commonly used devices. When a particular switch corresponding to a decimal number (0 to 9) is pressed, the BCD code corresponding to that number is generated. This is the function of an encoder. Sometimes we prefer to see output in a decimal format. Then, the binary coded decimal (BCD) data are to be converted into its corresponding decimal form, and this reverse operation is done by a decoder circuit.

In optical domain, these circuits can also be designed, and so far various attempts have been made in this field. F.Mehdzadeh et al. have developed all optical encoder and decoder using microring resonator-based optical switches [1, 2]. TA Moniem designed all optical decoder and encoder using integrated 2D square lattice photonic crystals [3]. Y. Tian developed the same using two cascaded microring resonators [4]. S. Kaur developed optical decoder using semiconductor optical amplifier (SOA) based MZI [5]. A. Bhattacharyya et al. designed 2-to-4 optical decoder with the help of TOAD [6]. In this article, the authors propose a method to develop an all optical encoder and decoder exploiting frequency conversion and polarisation switching character of semiconductor optical amplifier (SOA), and frequency encoded data have been used to execute the operation. Till date, so many types of data encoding/decoding techniques have been well established, such as spatial encoding [7, 8], intensity encoding [9, 10], polarisation encoding [11] and phase encoding [12]. But all these existing techniques have their own limitations. The main drawback of photonic crystal-based

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design is that there arises problem in the context of coupling of these logic processors to the waveguide and devices. Major limitation of the intensity encoded data employed in SOA-MZI, TOAD and MMR-based design is that for long-distance data communication system intensity of the encoded data may fall due to so many reasons and when the intensity falls below the threshold value of the binary encoded high state, it may introduce bit error problems. Also it is very difficult to maintain state of polarisation, spatial coherence and particular phase angles with polarisation, spatial and phase encoded data, respectively. The most advantage of frequency encoded data is that frequency of a signal is the fundamental preservative character of it, and it remains unaltered irrespective of absorption, reflection, refraction, etc., especially in low optical power domain [13–16]. The authors have utilised this nature-gifted advantage and have used the optical beam of frequency ν_0 (say) as the binary ‘0’ state, and the optical beam of frequency ν_1 as the binary ‘1’ state to implement the optical encoder and decoder. Polarisation switching characters of SOA as well as frequency conversion property of SOA using the rotation of the state of polarisation of the probe beam have been exploited in this proposed scheme [15, 16]. The low power consumptions, high gain and high cascading efficiency of semiconductor optical amplifier make it a worthy choice over other established techniques. The article is organised as follows:

Section-1 is the introduction part of the proposed scheme. In section-2, switching action and frequency conversion properties of the SOA have been explained. Section-3 covers the design of the optical encoder circuit and explains the operation of it supported by the simulation results. Section-4 deals with the circuit design, its operation followed by the simulation results of the optical decoder

circuit. Section-5 is the discussion part of the proposed scheme.

Working principle of polarisation switch

The working principle of semiconductor optical amplifier-based polarisation switch (PSW) is presented here in this paper with the help of simple rate equation model proposed by Dorren et al. [17], and using Fig. 1. To get the switching action of PSW, a high intensity pump beam is injected into the SOA. Another beam of comparatively low intensity is used as the probe beam after being attenuated by an attenuator. Polarisation controller (PC) has been used to control the state of polarisation of the probe beam of the SOA. A polarisation beam splitter (PBS) is used to split the output beam of the SOA into two components: a vertical component (V) called ‘TE’ mode, and a horizontal component (H) called ‘TM’ mode. Orientation of the electric field of the probe beam is adjusted approximately 45 degrees with the orientation of the active layer of the SOA.

When the pump beam is not applied, these two components of the probe beam move through the active region of the SOA with equal velocities and interfere constructively at the output end and delivers maximum power at output port-2, and no power is obtained at the output port-1. But with the application of pump signal of power more than 0.4 mW, these two components interfere destructively at the output port-2 and consequently no beam appears at port-2, and maximum power is developed at port-1 corresponding to the probe beam of that frequency [17–22].

The anisotropic gain of SOA depends mainly on the carrier dynamics and it can be expressed as

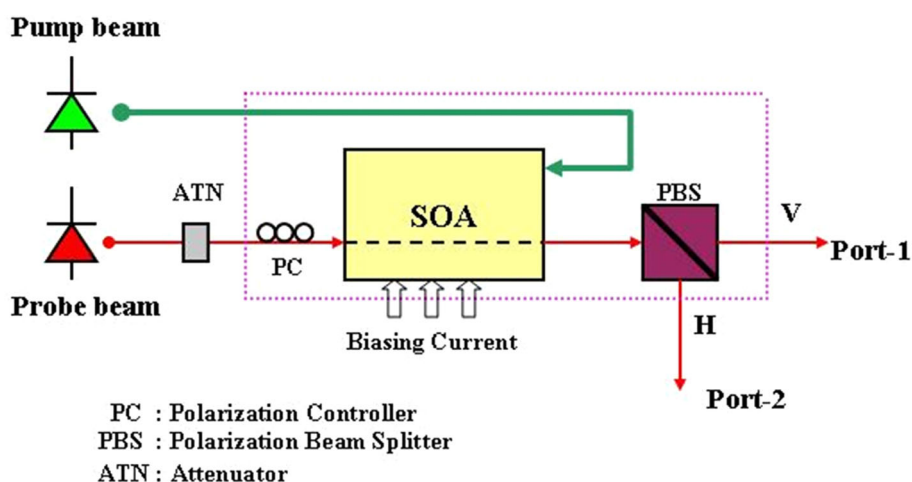


Fig.1 Polarisation switching action of SOA

$$g^{TE}(z, t) = \xi^{TE} [n_c(z, t) + n_x(z, t) - N_0] \tag{1}$$

$$g^{TM}(z, t) = \xi^{TM} [n_c(z, t) + n_y(z, t) - N_0] \tag{2}$$

This gain coefficient remains almost constant ($\xi_0^{TE/TM}$) for low power of the input signal, but for highly intense optical beam, it became a varying function of intensity ‘S’, and can be expressed as

$$\xi^{TE/TM} = \xi_0^{TE/TM} * 1 / (1 + \epsilon S^{TE/TM}) \tag{3}$$

In Fig. 2, we have shown how the gain for TE and TM mode varies with the input pump beam power.

The phase difference between TE and TM mode is given by

$$\Delta \varphi = \frac{1}{2} (\alpha^{TE} \Gamma^{TE} g^{TE} / v_g^{TE} - \alpha^{TM} \Gamma^{TM} g^{TM} / v_g^{TM}) L \tag{4}$$

Now the resultant output probe power is

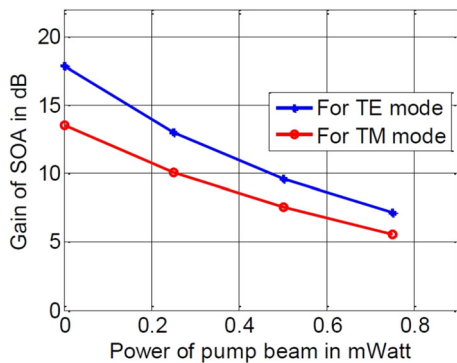


Fig.2 Variation of gain of TE and TM mode with respect to input pump beam power

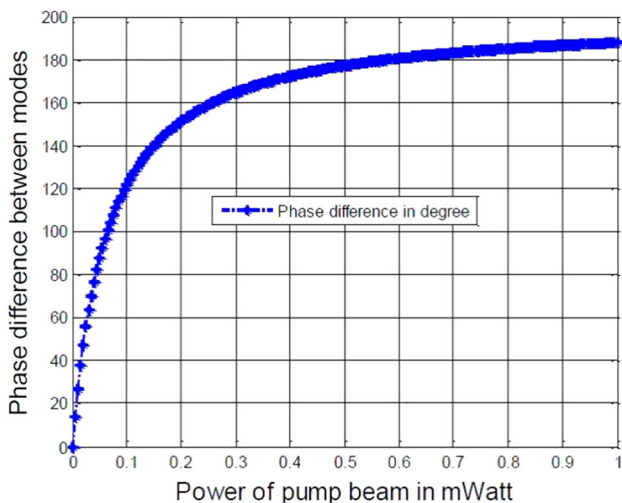


Fig.3 Variation of phase difference at the output of the PSW with power of the pump beam

$$P_{out} = P_{out}^{TE} + P_{out}^{TM} + \sqrt{P^{TE} P^{TM}} \text{Cos}(\Delta \varphi) \tag{5}$$

For a biasing current of 160 mA, the phase difference between two modes with the input power of the pump beam is shown in Fig. 3. Variation of the output power of the probe beam at port-1 and port-2 of PSW is also shown in Fig. 4. In the absence of the pump beam, port-2 of the PSW is in ‘ON’ state, and in the presence of the pump beam, it becomes ‘OFF’ state and complementary features is seen in port-1 of the PSW.

The values of some useful parameters used for SOA simulation are: $\Gamma^{TE} = 0.2, \Gamma^{TM} = 0.14,$

$$\alpha^{TE} = \alpha^{TM} = 5, \quad \xi^{TE} = 7.0 \times 10^{-9} \text{ps}^{-1},$$

$$\xi^{TM} = 6.5 \times 10^{-9} \text{ps}^{-1}, \quad v_g^{TE} = v_g^{TM} = 100 \mu\text{m}/\text{ps},$$

$$F = 0.5, N_0 = 10^8,$$

$$L = 800 \mu\text{m}, \quad T_1 = 500 \text{ps}, \quad \alpha_{int}^{TE/TM} = 0.27 \text{ps}^{-1},$$

$$e = 1.6 \times 10^{-19} \text{C}, \quad \epsilon = 10^{-7} \text{ per photon.}$$

Optical circuit design of Encoder and it’s operation

Optical circuit of our proposed ‘Encoder’ is shown in Fig. 5. The encoder circuit comprises four polarisation switches PSW0, PSW1, PSW2 and PSW3; four multiplexers (MUX) M0, M1, M2 and M3, and ten switches, namely S_0, S_1, \dots to S_9 . All the switches are fed by the optical beam of frequency v_1 ; all the input probe beam ports of the PSWs are fed from a common power source of optical beam of frequency v_0 . In ON state of a switch, optical beam passes through its respective MUX’s, and it is split up into two parts. One part of the output of the MUX serves as the pump beam of its corresponding PSW and the other part is connected to the port-2 of the output of its

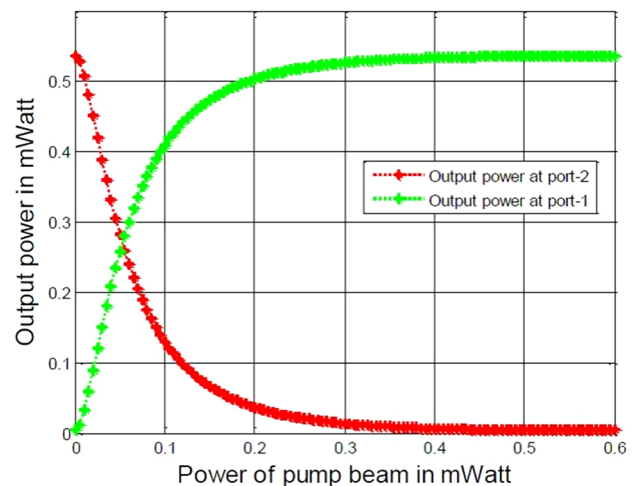
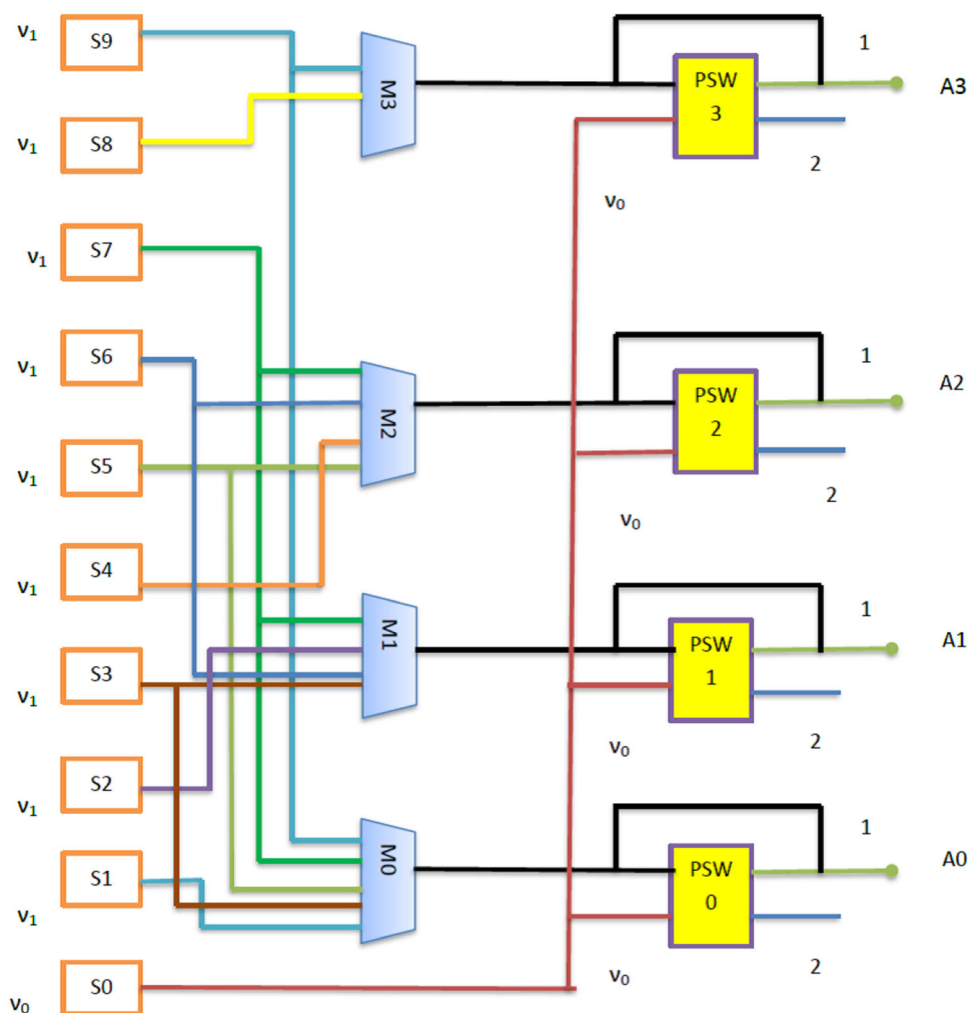


Fig.4 Variation of power at port-1 and port-2 with respect to the power of the pump beam

Fig.5 Schematic diagram of optical encoder circuit



corresponding PSW directly. All the output port-1 of each PSW remains open and it gives the complementary output of port-2. In Fig. 5, all the outputs A3, A2, A1 and A0 are taken from the port-2 of the respective PSWs. Output corresponding to the input decimal data from a specific switch as obtained in frequency encoded binary form is 'A3 A2 A1 A0'. Therefore according to our circuit connection, in the absence of the pump beam (OFF state of all switches S) output port-2 of all the PSWs gives beam of frequency v_0 , and no beam is obtained in port-1 of each PSW. On the other hand, if a pump beam be present (obtained from ON state of a switch S) in a PSW, one part of it switches the probe beam of frequency v_0 from port-1 to port-2, and another part of the pump beam directly reaches the port-2 (designated as output A) and gives output beam of frequency v_1 .

Now the operation of the encoder circuit is explained below with some specific cases of input decimal data (9,4,1,0) as below with the help of Fig. 5.

Case 1: When switch '9' is pressed

In this case, the input signal of frequency v_1 after passing through the MUX M3 reaches PSW3 directly and gives the output beam of frequency v_1 as MSB at A3 and port-2 of PSW3. Similarly, the input beam of frequency v_1 after passing through M0 serves as the pump beam of PSW0. In the presence of pump beam of sufficient intensity in PSW0, the probe beam of frequency v_0 is switched to port-2, giving the output A0 the optical beam of frequency v_1 . Here, PSW2 and PSW1 do not receive any pump beam, and consequently, the probe beam of frequency v_0 will appear at A2 and A1 via port-1 of the PSW2 and PSW1, respectively. Therefore, output frequency encoded BCD corresponding to decimal number 9 is.

$$v_1 \ v_0 \ v_0 \ v_1.$$

Case 2: When the decimal number is '4'

The input signal with frequency v_1 passing through M2 splits into two parts, one of which directly gives the output

A2 as ν_1 , and the other part serves as pump beam for PSW2. In the presence of pump beam of sufficient intensity in PSW2, the probe beam of frequency ν_0 is switched to port-2 giving the output A2 as ν_1 and all other PSWs (PSW2, PSW1, PSW0) not receiving any pump beam give frequency ν_0 at output A3, A1 and A0.

Case 3: For the conversion of decimal number ‘1’

The input signal with frequency ν_1 after passing through M0 divided into two parts, one part gives the output A0 and the remaining part serves as pump beam for PSW0. In the presence of pump beam of sufficient intensity in PSW0, the probe beam of frequency ν_0 is switched to port-2 giving the output A0 as ν_1 and all other PSWs (PSW3, PSW2, PSW1) not receiving any pump beam give frequency ν_0 at output A3, A2 and A1.

Case 4: When switch ‘0’ is pressed

In this case, all the PSWs (PSW3, PSW2, PSW1 and PSW0) not getting any pump beam give the frequency ν_0 at all the outputs A3, A2, A1 and A0. Therefore, the output frequency encoded BCD data corresponding to decimal number 0 will be $\nu_0\nu_0\nu_0\nu_0$.

In the similar way, we can get the frequency encoded BCD data output for rest of input decimal numbers (Table 1).

Simulation results of output power spectra for the optical encoder for different decimal numbers are shown in Fig. 6. Here, MATLAB software is used for simulation purpose. We use Gaussian pulse to represent the power at the outputs. Here, ‘0’ is represented by an optical beam with wavelength 1557 nm (corresponding to a frequency of 1.9255×10^{14} Hz, i.e. ν_0) and ‘1’ is represented by an

optical beam with wavelength 1552 nm (corresponding to a frequency of 1.9317×10^{14} Hz, i.e. ν_1) [22, 23].

Optical circuit design of ‘Decoder’ and its operation

The proposed optical decoder circuit is shown in Fig. 7. It comprises of four de-multiplexers DEMUX (D0, D1, D2 and D3), ten multiplexers (M0 to M9), ten PSW switches (P0 to P9) and ten switches (0 to 9). Input signals are fed to four terminals (A0 to A3) and being channelised through two channels of DEMUX acts as pump beams of different PSWs after required frequency inversion by NOT gates. Another beam of frequency ν_1 is fed to PSWs as probe beam. If the input pump beam of the PSWs have sufficient intensity it will rotate the SOP of probe beam and switches it to the port-1 of PSW. Here, all the outputs are taken from port-1 of PSW switch. If we get ν_1 frequency at the output port, this after converted to intensity signal will make the switches ON. Now the operation the decoder circuit is explained in detail with the help of Fig. 7 for three specific cases.

Case: 1 $A3 = \nu_0, A2 = \nu_1, A1 = \nu_1, A0 = \nu_1$

Input beam of frequency ν_0 passes through channel-1 of D3 and converted into beam of frequency ν_1 (after frequency inversion by NOT gate). The other three input frequencies ν_1 channelised through channel-2 of D2, D1 and D0 result four beam of frequency ν_1 at the input of M7. These beams after passing through M7 behave as pump beam of PSW7 and resulting probe beam of frequency ν_1 at port-1 of PSW7. All other PSWs not getting the pump beam of sufficient intensity remain in OFF state, giving ν_1 frequency only at output terminal 7. Thus, ‘ $\nu_0 \nu_1 \nu_1 \nu_1$ ’ decodes the decimal number ‘7’ in the form of frequency encoded data.

Case: 2 $A3 = \nu_0, A2 = \nu_1, A1 = \nu_0, A0 = \nu_1$

In this case, only PSW5 gets the four beam of frequency ν_1 as the input pump beam so it only switches the probe beam of frequency ν_1 to port-1 and all other PSWs not getting the pump beam of sufficient intensity remain in OFF state. As a result, ν_1 frequency is only obtained at terminal 5.

Table 1 Presentation of decimal numbers in terms of BCD and frequency encoded bits

Decimal number	BCD	Frequency encoded bits
9	1001	$\nu_1 \nu_0 \nu_0 \nu_1$
8	1000	$\nu_1 \nu_0 \nu_0 \nu_0$
7	0111	$\nu_0 \nu_1 \nu_1 \nu_1$
6	0110	$\nu_0 \nu_1 \nu_1 \nu_0$
5	0101	$\nu_0 \nu_1 \nu_0 \nu_1$
4	0100	$\nu_0 \nu_1 \nu_0 \nu_0$
3	0011	$\nu_0 \nu_0 \nu_1 \nu_1$
2	0010	$\nu_0 \nu_0 \nu_1 \nu_0$
1	0001	$\nu_0 \nu_0 \nu_0 \nu_1$
0	0000	$\nu_0 \nu_0 \nu_0 \nu_0$

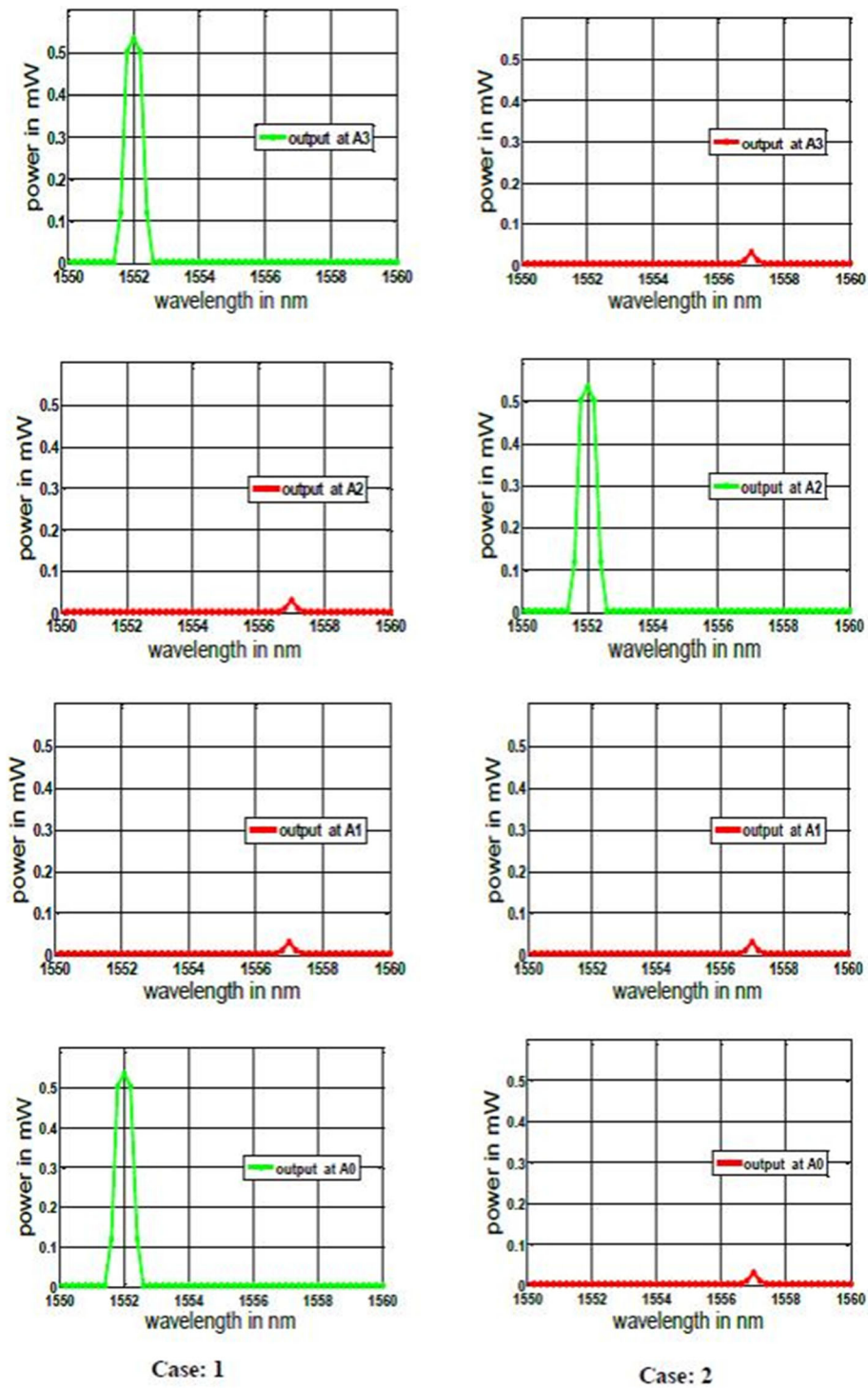


Fig.6 Simulation results of optical encoder circuit

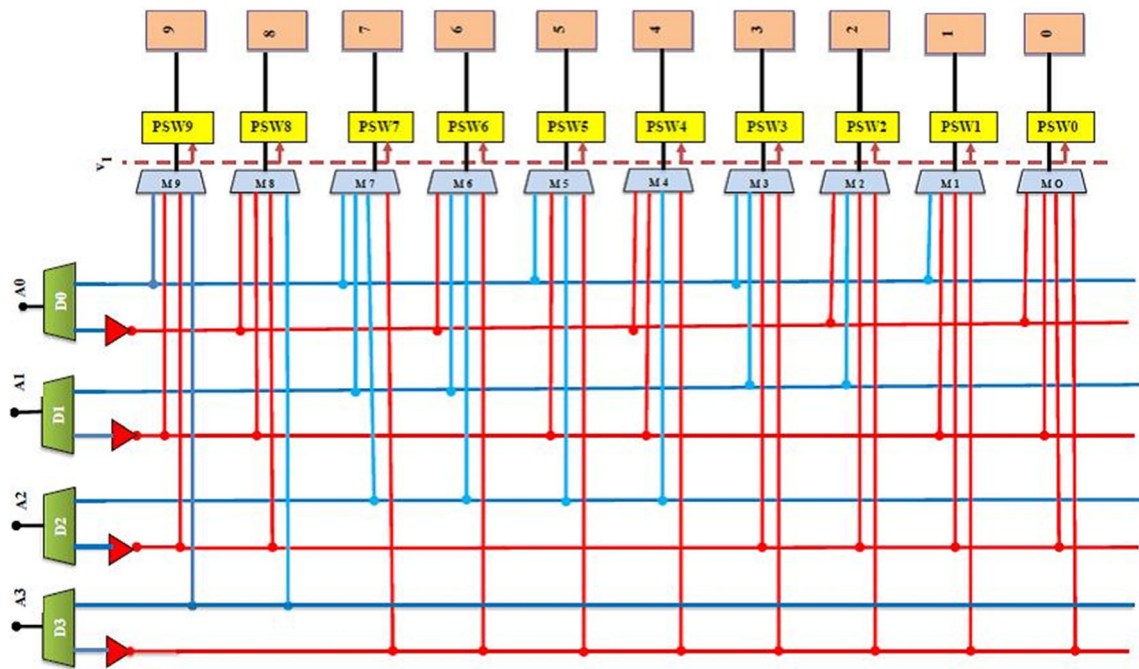


Fig.7 Schematic diagram of optical decoder circuit

Case: $3 A3 = v_0, A2 = v_0, A1 = v_1, A0 = v_1$

Here, only PSW3 gets four pump beam so it switches the probe beam to its port-1 and all other PSWs remain OFF. At terminal 3, we only get the frequency v_1 . In this case, frequency encoded data ‘ $v_0 v_1 v_1 v_1$ ’ decode decimal number ‘3’.

Similarly, we can explain the other possible cases. In the simulated input–output spectrum, the proposed decoder circuit is shown in Fig. 8.

Conclusions

We can use commercially available JDS uniphase SOA for using it as polarisation switch (PSW). In such case, minimum 0.5 mW pump power is required to switch the probe beam from port-2 to port-1, and the probe beam power should be 0.03 mW [17, 18]. The operational speed of the proposed circuits depends on the switching time of SOA-based PSW. It is very much possible to archive an operational speed of 100 GB/s, i.e. the switching time of 0.01 ns by proper biasing of PSW. It is to be noted that the switching delay of each PSW is 0.01 ns, and that of a MUX is of the order of 0.01 ns [24, 25, and 26]. Apparently, so many circuit components are present and it seems to degrade the processing speed. But due to parallel processing, the operational speed is not affected so much. In case of encoder, for any particular operation, maximum three MUX and four PSW simultaneously remain in action.

So maximum expected propagation delay is 0.07 ns. Similarly for decoder circuit, four DMUX and one PSW simultaneously act, so maximum propagation delay is 0.05 ns. In the C-band, the gain of SOA remains constant. So for encoding the data, it is the best choice to select the frequencies from C-band. Here, the encoded frequencies [v_0 (1557 nm), v_1 (1552 nm)] are in C-band. We know that in C-band the polarisation-dependent gain is very low. Therefore, using frequencies of the input beams in this regime can make this scheme more attractive and useful in optical network [18, 27–29]. In the proposed encoder circuit, some of the input beams are spitted into two or three parts. So their powers should be properly adjusted to have the pump beam of sufficient power. For example, the beam coming from switch ‘7’ is spitted into three parts, so before splitting the power of this beam should be at least 0.3 mW. Similarly, the beam coming from switch ‘9’ should be of at least 0.4mW. The beam coming from switch ‘0’ is spitted into four parts and serves as probe beams for four PSWs. So its power should be greater than 0.12mW [28].

Here in this proposed work, some multiplexer and demultiplexers are used to develop the optical circuits. The optical signal losses due to these MUXs/DEMUXs are not taken into consideration. Time delay of signals in optical communication is a very big issue. This delay can be introduced due to the passing of signals through optical fibres of different lengths. To overcome this problem, the lengths of the optical fibres used for transmission of signals are should be same, and this time should be less than the switching time of PSW. Here, we ignore the ASE and

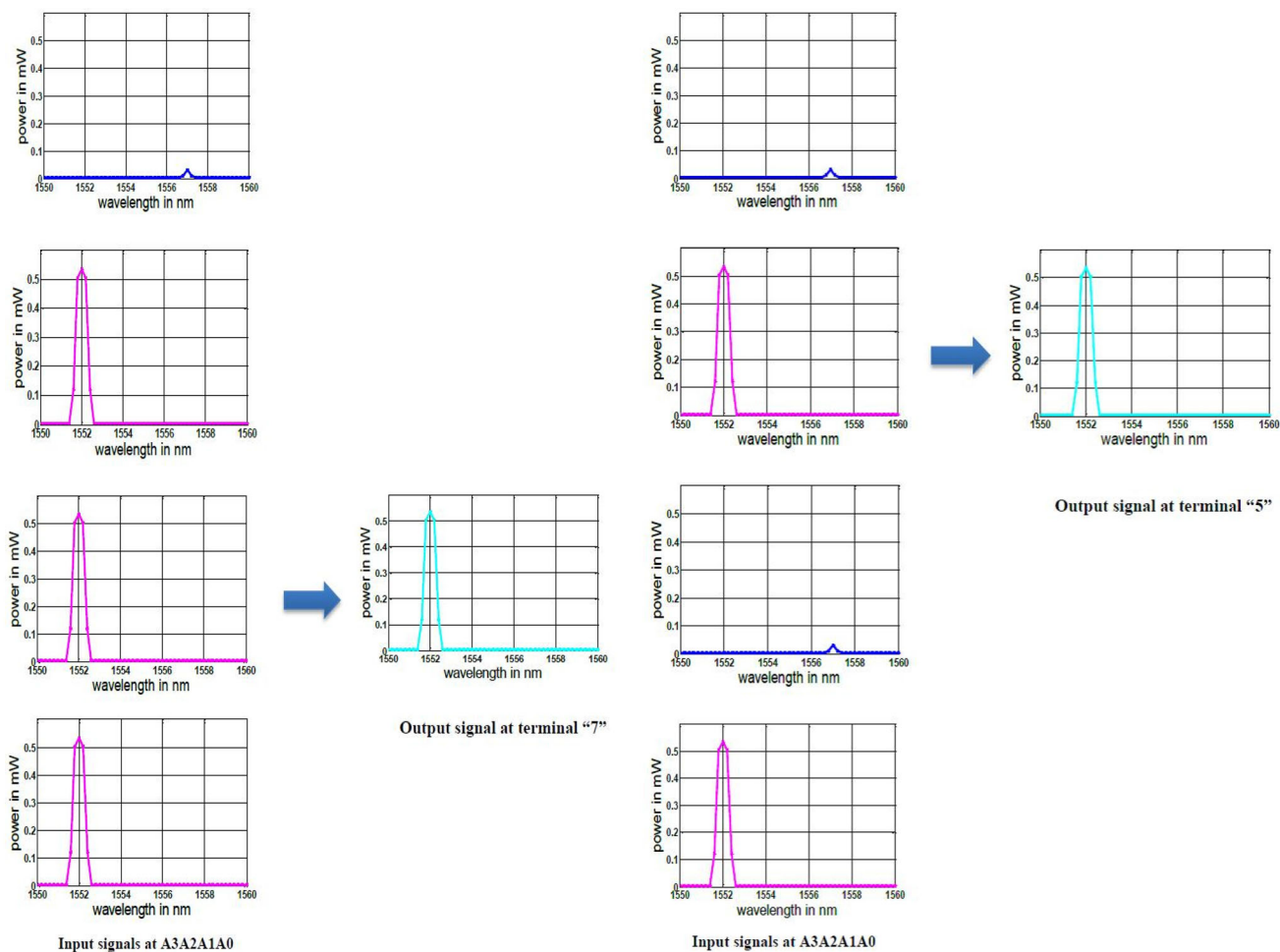


Fig.8 Simulation results of optical decoder circuit

signal-to-noise ratio (SNR) problem keeping in mind the various advantage of frequency encoding technique. It is assumed that as SOA operates in the linear region, this type of noise is low, and this does not create too much problem in cascading of SOAs. However, proper amplifier, attenuator and beam splitter are used in this scheme to suppress the noise up to some extent. Overall, considering the various aspects of uses of encoder and decoder circuit in

communication technology and the beauty of use of frequency encoded data for encoding purpose with very high switching speed of PSW makes the proposed scheme very attractive and effective.

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