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Abstract. A novel approach for all-optical digital encoder for both binary-to-gray code and gray-to-binary code have been proposed. Design is based on the basic concept of digital encoder using the exclusive OR (XOR) addition. The XOR gate used in these encoders has been implemented using differential phase modulation between two arms of the Mach-Zehnder interferometer (MZI), in which a semiconductor optical amplifier is placed symmetrically in both arms of MZI. For the most severely degraded output bit, i.e., least significant bit for gray-to-binary encoder, the extinction ratio obtained is 2.35 while the minimum bit error rate is zero at 10 GB/s. For the second most significant bit of gray-to-binary encoder and for all the three bits except the most significant bit of binary-to-gray encoder, the extinction ratio obtained is around 27 dB. For the most significant bit, as input and output bits are same, the extinction ratio is very high, approaching infinity. [DOI: 10.1117/1.OE.52.3.035202]

Subject terms: semiconductor optical amplifier; Mach-Zendher Interferometer; gray code; binary code; digital encoder.

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1 Introduction and Principle of Operation

This paper deals with digital encoder in all-optical domains. It is used to convert the code from binary to gray and gray to binary. These coders can be used with sensors and type of sensors will decide whether total encoder is incremental or absolute. In incremental encoders, position is not uniquely defined and homing is required to determine the absolute position, while in absolute encoder, there is a unique value for each position and homing is not required.

Optical encoders are used to measure displacement and position. Measurement can be linear or rotary. For both linear and rotary measurements encoder have binary or gray coded scales. The binary encoder uses a standard binary progression to indicate position. For each transition, from one position to the next, the binary output signal increments by one or decrements if the movement is in the opposite direction, thus giving a unique positional address anywhere around the encoder scale. Changes in address, whether the binary signal increases or decreases, indicate the direction of movement. Problems can arise with the binary encoder in position measurement applications because the positional transition from one position to the next can cause more than one bit of information to change at the same time.[1,2] The gray scale is designed so that all positional transitions only involve the change of one bit of information at a time, an increment or decrement depending on the direction of movement. The actual position and consequently direction, is determined through the unique address code for each position.

To sort out this problem, all-optical encoders, binary to gray and gray to binary, are proposed in this paper. All-optical encoders, binary to gray and gray to binary, proposed in this paper are based on all-optical exclusive OR (XOR) gate. The schematic diagram used for simulation of all-optical XOR gate is shown in Fig. 1. This design is using differential phase modulation in semiconductor optical amplifier-Mach-Zehnder interferometer (SOA-MZI) configuration. The main parameters used in this design are shown in Table 1. The encoders proposed in this paper can be used if the output is in binary form and the desired one is gray, i.e., binary to gray encoder and similarly if O/P is in gray form and desired one is binary, i.e., gray to binary encoder in all-optical domain. Gray code is a code with the property that there is one and only one bit change between any two neighboring numbers. More precisely it has both the reflective property and the unit distance property. Setups used for numerical simulation of binary to gray and gray to binary are shown in Figs. 2 and 3, respectively. To the best of our knowledge the only work which has been done on all-optical 4-bit gray to binary coded decimal converter is reported in Ref. 3. In this reference paper the encoder is designed using all-optical NOR gate based on cross gain modulation in SOA. The Q factor quoted in this paper was four with 20 dB extinction ratio at 2.5 Gb/s. While in our simulation work the minimum Q factor

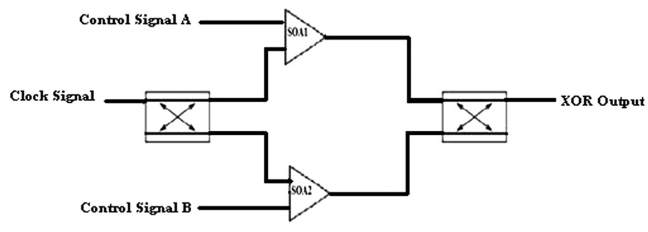

Fig. 1 Configuration of all-optical XOR gate using SOA-MZI.

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Table 1 Important parameters used in XOR gate design.

SOA parameters	
Injection current	300 mA
Active region length	0.6 mm
Optical confinement factor	0.45
Active refractive index	3.22
Coupler's parameters	
I/P and O/P coupling loss	0 dB
I/P and O/P facet reflectivity	5e-005
Signal power	
Control signal power	20 dBm
Clock/probe signal power	2 dBm

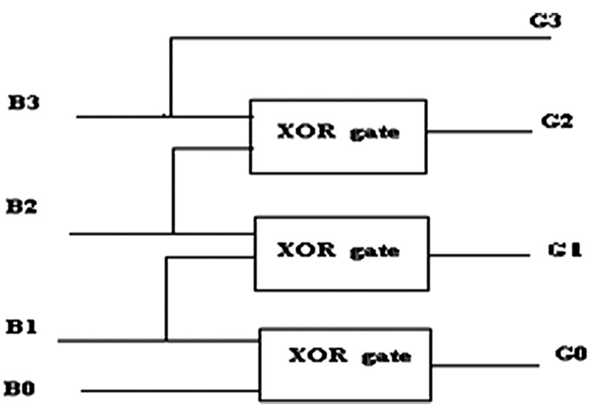

Fig. 2 Setup for numerical simulation of binary-to-gray encoder.

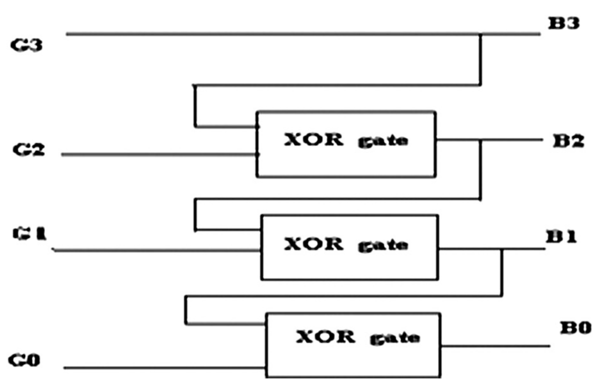

Fig. 3 Setup for numerical simulation of gray-to-binary encoder.

demonstrated is 18.37 dB with bit error rate (BER) 7.69E-076 and extinction ratio of 27.6 dB at 10 Gb/s. Minimum extinction ratio for the severely degraded least significant bit for gray to binary encoder is 2.35 dB. Similar works on all-optical combinational circuits based on SOA in filter configuration are reported in research papers.[4,5] Performance of all-optical logic gates/circuits can be optimized using SOA-MZI configuration.[6] Therefore SOA-MZI configuration is used for the design of all-optical XOR gate used in the proposed all-optical encoders.

Truth table for 4-bit binary-to-gray encoder is shown in Table 2. The same table can be used for 4-bit gray-to-binary encoder using in reverse direction. Simplified expression for gray code bits in terms of input binary digits for binary to gray encoder and similar expression for output binary code bits for gray-to-binary encoder can be obtained using Karnaugh map.

After simplification, steps for binary-to-gray encoder are:

1. The most significant in the gray code remains the same as that in the corresponding binary number.

Table 2 Truth table for binary-to-gray and gray-to-binary encoder.

Four bit binary numbers				Four bit gray numbers			
B0	B1	B2	B3	G0	G1	G2	G3
0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	1
0	0	1	0	0	0	1	1
0	0	1	1	0	0	1	0
0	1	0	0	0	1	1	0
0	1	0	1	0	1	1	1
0	1	1	0	0	1	0	1
0	1	1	1	0	1	0	0
1	0	0	0	1	1	0	0
1	0	0	1	1	1	0	1
1	0	1	0	1	1	1	1
1	0	1	1	1	1	1	0
1	1	0	0	1	0	1	0
1	1	0	1	1	0	1	1
1	1	1	0	1	0	0	1
1	1	1	1	1	0	0	0

2. Add each adjacent pair of binary digit from most significant digit position to get the corresponding digit of the gray code, ignoring the carry.
   $G_n = B_n \oplus B_{n+1}$, where $n = 0,\ 1,\ 2$ for 4-bit encoder.

After simplification, steps for gray-to-binary code converter are:

1. The most significant in the binary code remains the same as that in the corresponding gray number.
2. Add each binary digit generated (from most significant digit position) in the gray code to the next adjacent position, ignoring the carry.
   $B_n = B_{n+1} \oplus G_n$, where $n = 0,\ 1,\ 2$ for 4-bit encoder.

2 Simulation and Results

A novel scheme for ultra-high speed all optical encoder, binary-to-gray and gray-to-binary encoder based on SOA-MZI configuration is proposed in this paper. In the first step of design, all-optical XOR gate has been designed using differential phase modulation in SOA-MZI configuration.[7] The truth table of this gate is verified on the basis of output power as well as in time domain with different input bit sequences. In the next step, 4-bit binary-to-gray encoder and gray to binary encoders are designed using this XOR gate. By numerical simulation, the truth tables of binary-to-gray and gray-to-binary encoder are verified on the basis of power level output. For analyzing the performance of this encoder in detail, the BER analysis has been performed. Maximum Q factor, minimum BER, and extinction ratio for different output bit positions are calculated at 10 GB/s. The results obtained at different bit positions are mentioned in Table 3 for binary-to-gray and Table 4 for gray-to-binary encoder. Eye pattern at different O/P bit positions are shown in Figs. 4 to 7 for binary to gray and Figs. 8 to 11 for gray to binary encoder. Ideal results are obtained for most significant bit position as this remains same for 4-bit gray and binary numbers and hence connected directly from input to output.

Table 3 Performance parameters of binary-to-gray encoder at different output bit position.

Output bit position	Max. Q factor	Min. BER	Ext. ratio (dB)
G0	48.82	0	27.8
G1	50.00	0	27.1
G2	47.71	0	27.1
G3	18.38	6.03E-076	—

Table 4 Performance parameters of gray-to-binary encoder at different output bit position.

Output bit position	Max. Q factor	Min. BER	Ext. ratio (dB)
B0	40.03	0	2.35
B1	45.67	0	4.80
B2	41.48	0	27.1
B3	18.37	7.69E-076	—

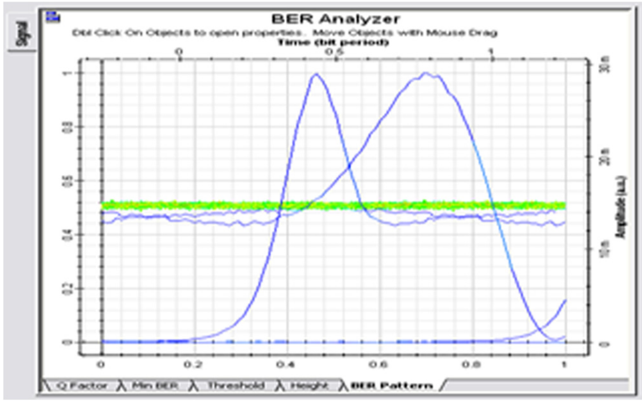

Fig. 4 BER pattern for least significant bit G0 of binary-to-gray encoder.

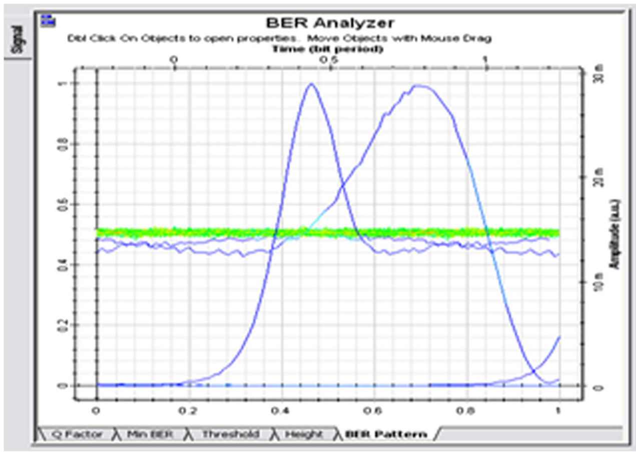

Fig. 5 BER pattern for bit G1 of binary-to-gray encoder.

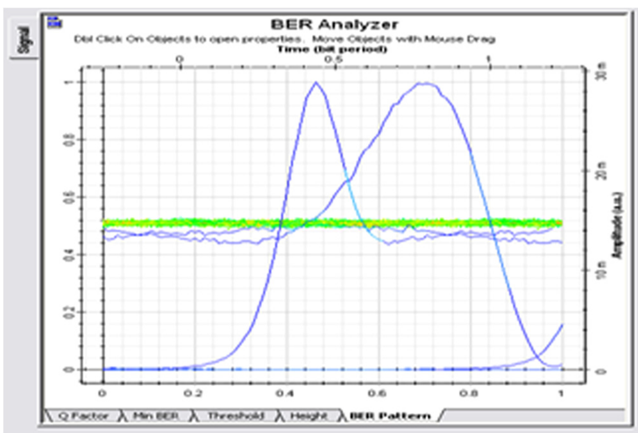

Fig. 6 BER pattern for bit G2 of binary-to-gray encoder.

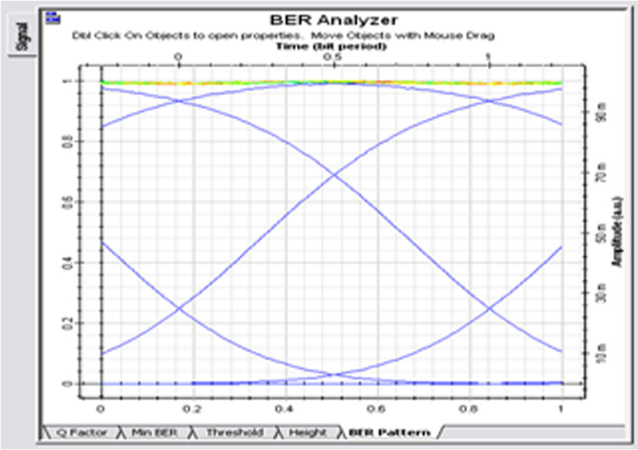

Fig. 7 BER pattern for output bit G3 of binary-to-gray encoder.

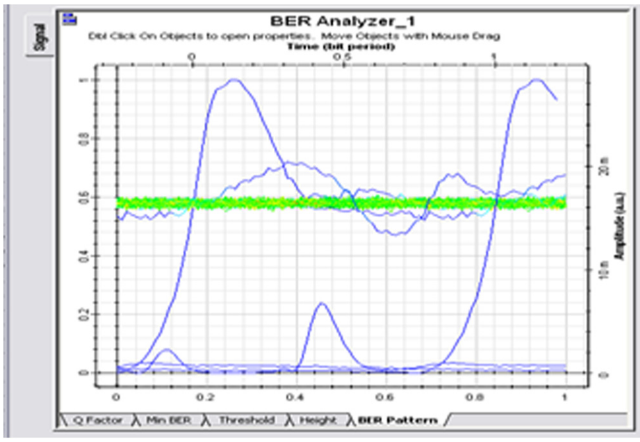

Fig. 8 BER pattern for least significant bit B0 of gray-to-binary encoder.

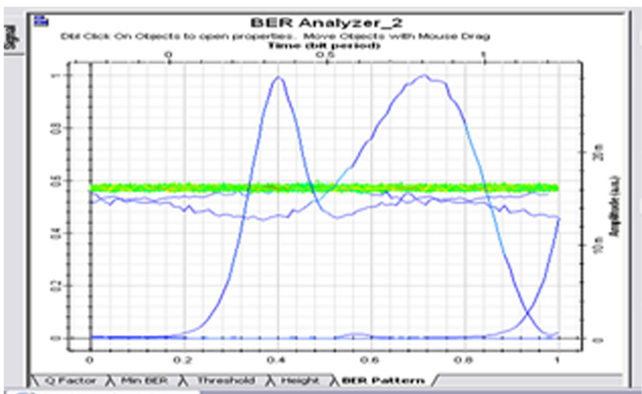

Fig. 9 BER pattern for output bit B1 of gray-to-binary encoder.

3 Conclusion

Performance of all-optical ultra-high speed binary-to-gray and gray-to-binary encoders has been evaluated for the first time in optical domain at 10 GB/s. Maximum Q factor, minimum BER, and extinction ratio for different output bit positions are evaluated. Eye diagrams are the simulation results with BER and maximum quality factor. These results can be interpreted using the general concept of eye diagram.

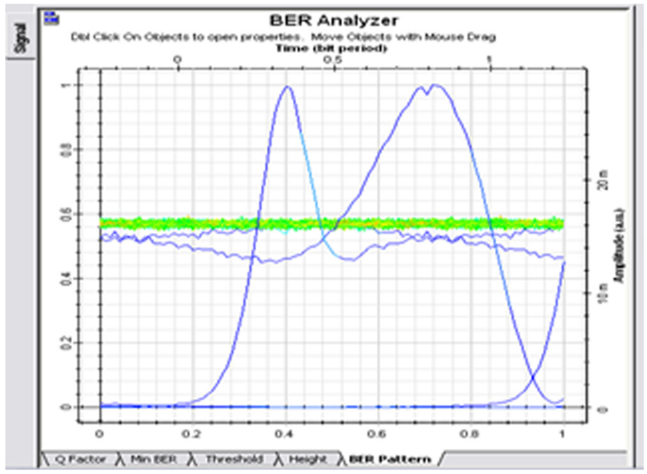

Fig. 10 BER pattern for output bit B2 of gray-to-binary encoder.

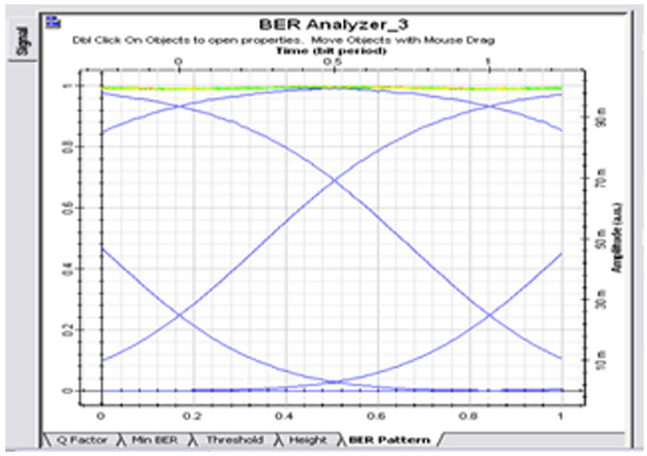

Fig. 11 BER pattern for output bit B3 of gray-to-binary encoder.

Vertical and horizontal opening of eye are sufficient to have the satisfactory performance. Vertical opening of eye represents the sampling instant of each pulse, where the pulse amplitude is at peak without interference. Horizontal opening or width of eye indicates the time interval over which the decision can be made.

Eye diagrams obtained for bits G_3 (MSB of gray code) and B_3 (MSB of binary code) are same and resemble with the theoretical one, which is justified as no conversion is involved in these bits.

Maximum extinction ratio obtained is 27.8 dB and for most of the bits it is 27.1 dB which is good enough for acceptable design. Truth table as given in Table 2 is verified on the basis of output power both for gray-to-binary and binary-to-gray encoder. BER analysis has also been performed for both the encoders. This paper can give the idea of implementing any combinational logic circuit in all-optical domain. Based on these criteria, different encoders can be designed in all-optical domain.

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