Quantum Dot Semiconductor Optical Amplifiers for Optical logic Applications

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ABSTRACT

Quantum-dot (QD) based semiconductor optical amplifiers (SOA) are important because they have high gain and short gain recovery time. The fabrication and performance of these devices will be described. All-optical Boolean logic functions AND, XOR and NOT using semiconductor optical amplifiers with quantum-dot active layers is studied at 40 and 80Gb/s. A model of QD-SOA shows that the QD excited state and wetting layer serve as reservoir of carriers, and, the ultra fast carrier relaxation from these layers, results in high speed Boolean logic operations.

Introduction

Extensive research has been carried out on semiconductor optical amplifiers (SOA) with quantum dot (QD) active region over the last ten years. Like SOAs with multi quantum well (MQW) active region, the peak of the gain spectrum in QD amplifiers depend on the size of the dots in addition to the material composition of the dots, and, the material composition of the region in which the dots are embedded. In order to have sufficient optical gain, multiple layers of quantum dots are often used in the active (gain) region. The quantum dot semiconductor optical amplifiers (QD-SOA) have some advantages over conventional bulk or quantum well devices because of higher saturation power, faster gain recovery and large amplification bandwidth [1-8]. All of these features make QD-SOA device a promising component in high data rate all-optical switching and data processing applications.

The development of all optical logic technology is important for a wide range of applications in all optical networks, including high speed all optical packet routing, and optical encryption. An important step in the development of this technology is a demonstration of optical logic elements and circuits, which can also operate at high speeds. These logic elements include the traditional Boolean logic functions such as XOR, OR, AND, INVERT etc, and circuits such as parity checker, all-optical adder and shift register. Several articles on principles of all-optical logic have been published [9-16].

Quantum Dot based Semiconductor Optical Amplifier (QD-SOA)

The quantum dot material consists of dots (sometime irregular) of a semiconductor (e.g. InAs) embedded in another semiconductor (e.g. InGaAs). The growth process utilized for dot formation is generally the Stranski–Krastanov growth (S-K growth) process. Beyond a critical layer thickness, which depends on strain and the chemical potential of the deposited film, growth continues through the nucleation and coalescence of InAs (adsorbate) 'islands'.

The structure of a quantum-dot SOAs along with the scanning electron photomicrographs of the QD active region is shown in Figure 1[7]. The quantum-dot layers consist of InAs QDs (grown using S-K method by molecular beam epitaxy) embedded in InGaAs. The embedding layer affects the emission wavelength [8]. In order to obtain sufficient gain from the quantum dots, the quantum-dot layers are generally repeated a few times (10 in Figure 1). Generally, close stacking of quantum-dot layers causes vertical lining of dots (Figure (a)), which leads to strain accumulation. The researchers in [7-9] developed a technique to eliminate lining up (Figure 1 (b)) and hence strain accumulation. This leads to improved crystal quality. This material (Figure 1) was processed into a ridge waveguide structure 10 μm wide and 2.5 mm long. The facet reflectivity was reduced by applying antireflection (AR) coating. The entire structure is grown on a n-GaAs substrate. Buried heteristructure based QD SOAs have been fabricated.

The QD SOAs have more than 30 dB fiber to fiber gain, saturation power of 20 dBm and noise figure of 5 dB. They are used in transmission and optical logic experiments and have superior performance compared to regular or MQW based SOA device.

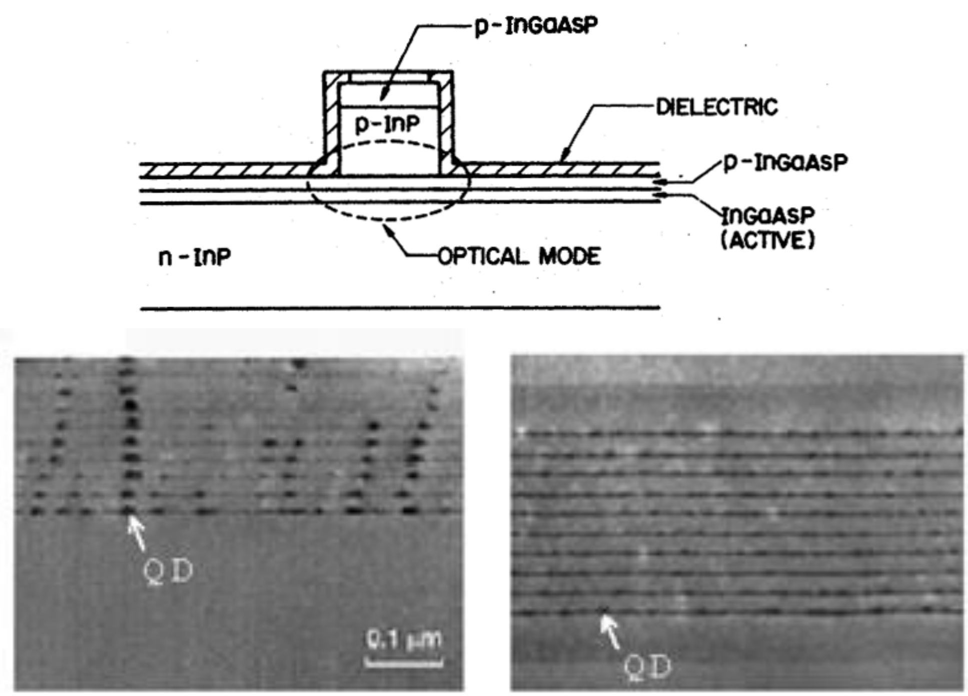


Figure 1: Structure of ridge waveguide type quantum dot (QD) SOA. Bottom figure show two types of QDs (a) aligned quantum dots (b) nonaligned QDs [7]

Optical Logic XOR

An ultrafast all-optical exclusive OR (XOR) logic gate is an important component in OTDM communication networks. Its truth table is shown in Table 1. It can be used in all-optical signal processing such as bit pattern matching, pseudo random number generation and label swapping. As is the case for electronic logic gates, all-optical logic gates fundamentally rely on nonlinearities. So far, methods utilizing the nonlinearities of optical fiber and semiconductor optical amplifier (SOA)[17-19] have been used to demonstrate all optical XOR functionality. The all-optical logic gate based on the nonlinearities of optical fiber has the potential of operating at terabits per second due to very short relaxation times (<100 fs) of its nonlinearity. The disadvantages of optical fiber are its nonlinearity is weak, and, long interaction lengths or high control energy is required to achieve reasonable switching efficiency.

Data B	Data A	Output XOR, AND
0	0	0, 0
1	0	1,0
0	1	1,0
1	1	0, 1

Table 1: The Truth Table of XOR, AND

Semiconductor optical amplifier has the advantages of high nonlinearity and ease of integration. All optical logic XOR has been demonstration using SOA based Mach-Zehnder interferometer (SOA-MZI) [15-19] is discussed here. It has many attractive features such as low energy requirement, low latency, high stability and compactness. This makes SOA-MZI suitable for producing complex photonic logic circuits such as shift registers.

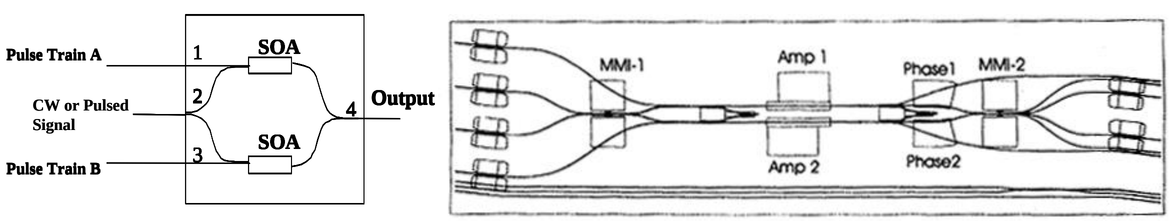


Figure 2: Schematic set up of the XOR gate in the left figure and implementation using multimode interference couplers (MMI) in the right figure. The phase shifters are needed to balance the phase difference between the two arms. The waveguides are angled at the facet to reduce the effect of reflections from the facet.

The optical XOR gate with SOA-MZI consist of a symmetrical MZI with two SOAs placed in upper and lower arms of the interferometer as shown in Figure 2. To perform the XOR function as shown in the truth table, two optical control beams A and B are injected into the two arms separately. The signal, a clock stream of continuous series of “1”`s or a CW beam is split into two equal parts and injected into the two SOAs. Initially the MZI is unbalanced i.e. when A=0 and B=0, the signal at port 2 traveling through the two arms of the SOA acquires a phase difference of π when it recombines at the output port, thus the output is “0”. When A=1, B=0, the signal traveling through the arm with signal A acquires a phase change due to the cross phase modulation (XPM) between the pulse train A and signal, and the signal traveling through the lower arm does not have this additional phase change. This results in an output “1”. The same phenomenon happens if A=0 and B=1. However, when A=1 and B=1 the phase change for the signal traveling both arms are equal, hence the output is “0”. When the phase shift is optimum, the best contrast ratio is achieved at the output port. Mode locked laser pulses are used to produce the signals. Figure 3 shows the results of the all-optical XOR logical gate operation at 40 Gb/s both for patterned pulses and pseudo-random pulses.

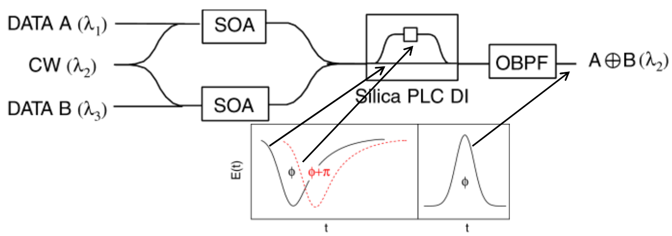


Figure 3: Schematic of the experimental set up using patterned pulses. The data signals are obtained from mode locked lasers. OBPF – Optical band pass filter.

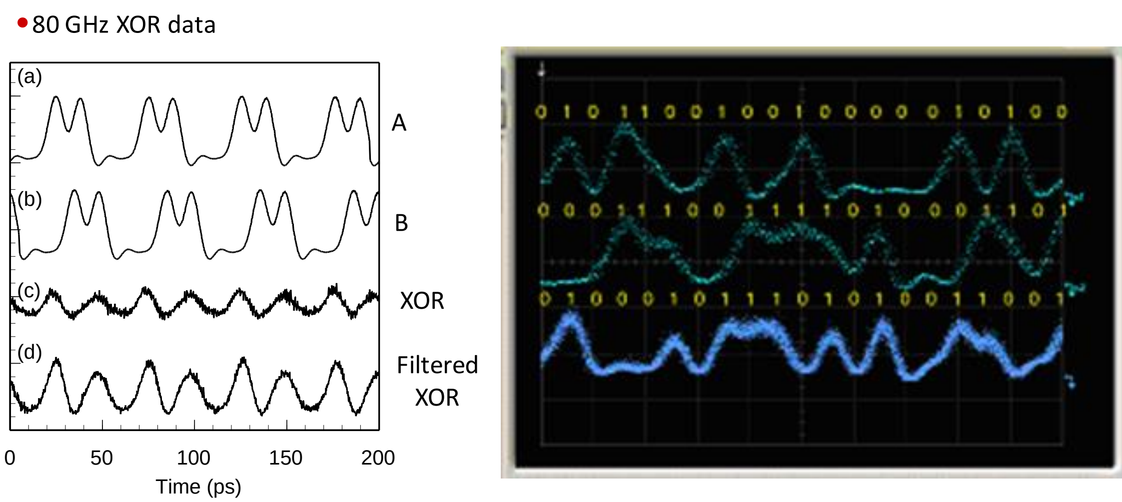


Figure 4: Results of XOR. Note the band pass filter improves signal to noise ratio. The figure on the right is for 80 Gb/s pseudo–random pulses.

Optical Logic AND

The truth table for AND operation is shown in Table 1. The schematic of the experiment and results are shown in Figures 5.

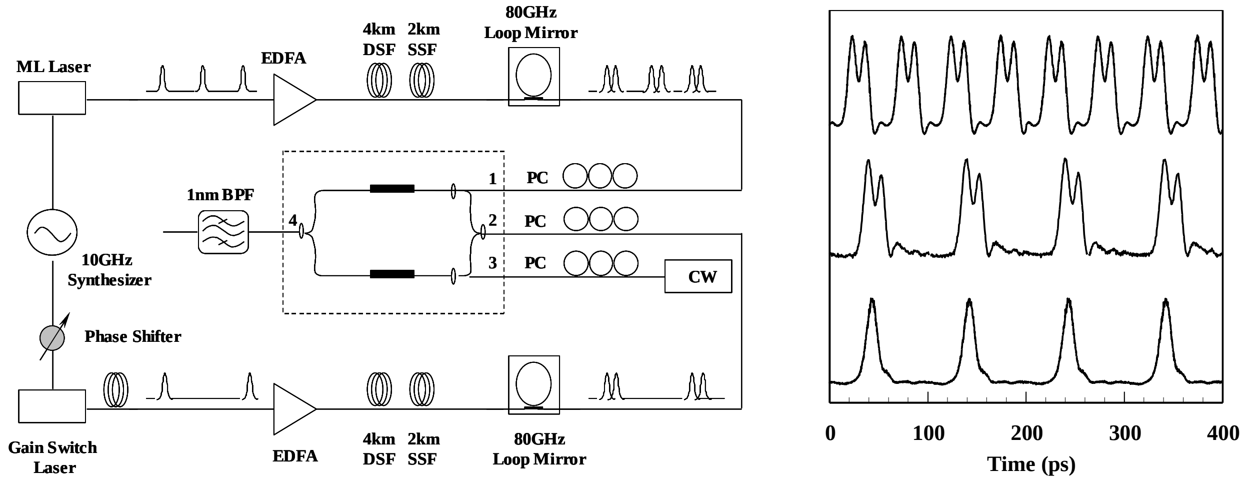


Figure 5: Experimental set up for AND operation. ML – Mode Locked, EDFA – erbium doped fiber amplifier. DSF – dispersion shifted fiber, SSF – single mode fiber. Results of AND operation at 80 GHz using patterned signals (left). Top lines are signals A and B and bottom shows AND operation

Optical Logic OR

OR operation is carried out using a SOA based delayed interferometer. The schematic of the experimental set up and the results are shown in Figure 6.

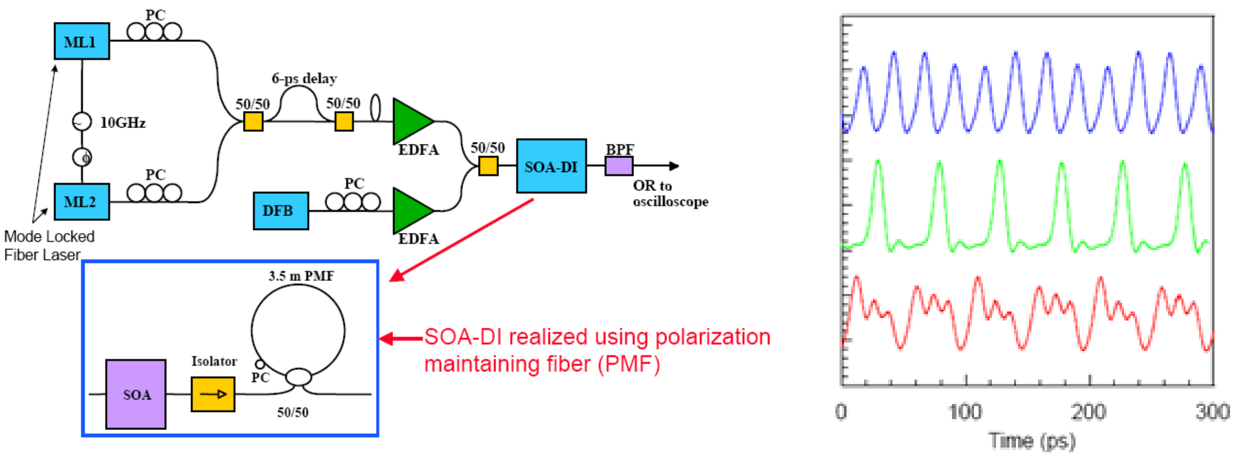
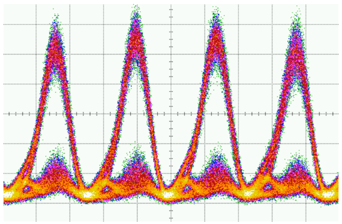


Figure 6: Schematic of the experimental set up and the OR result using patterned pulses. The input A (1010) and input B is (0100), the OR output is (1110). The OR operation uses 80 GHz pulses.

Optical Logic INVERT (NOT)

The schematic of the experiment and the results are shown in Figure 7. Input data signal A is coupled into SOA with 80 GHz clock sequence, Nonlinear gain/phase modulation of clock (shown CW in Figure) in SOA takes place when data signal present. The DI (delayed interferometer) splits output signal, delays one component. Data recombine/interfere at output coupler. DI for this demonstration is a hybrid integrated silica waveguide device



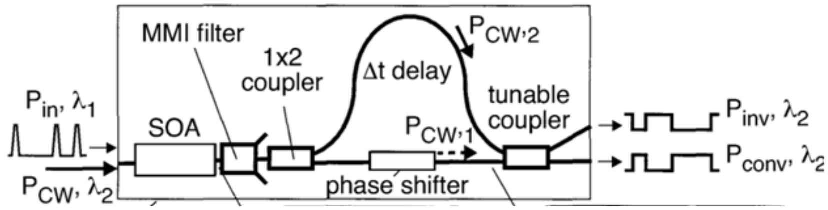


Figure 7: Schematic of the experimental set up is on the left. The right figure shows the result. The experimental result shown is with 80 GHs clock signal. The different clor in the bottom is the inverted result "0" of the "1".

Summery

The QD-SOA i.e. semiconductor optical amplifier with a quantum dot region is an important device for high speed optical signal processing. Due to its high saturation power and fast gain and phase recovery times, several experimental results have shown better high speed performance of QD-SOAs compared to SOAs with bulk active or multiquantum well active region. Thus Mach-Zehnder interferometer (MZI) devices using quantum dot SOAs are likely to provide a higher speed operation compared to that for similar devices using regular SOAs. All optical Boolean logic operations at high speed using MZI-SOAs has been demonstrated.

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