ABSTRACT

The optical switches and fabrics with switching time in the order of femto seconds and less than are required to realize networks based on Dense Wavelength Division Multiplexing (DWDM), Optical Time Division Multiplexing (OTDM) etc. Optical switches based on quantum dot structures inherently possess to provide such a high-speed responses. This paper brings out the switching times, impedances and insertion losses of both optical switch and fabric designed using Quantum Dot (QD) structures. The circuit model approach has been carried out for this analysis. The simulations are done with Saber sketch. 2X2 Total Internal Reflection (TIR) switch and 4X4 Spanke switch fabric have been considered as switch element and fabric for this work. The switching speed and insertion loss of 2.86fs, 22.85 fs and 8.997 dB, 17.94 dB are obtained for switch element and fabric respectively. These observed values are quite better than other non-all optical switches and comparable with all optical switch responses.

Keywords: Optical networks, switch element, switch fabric, quantum dots, switching time, insertion loss, circuit model.

1. INTRODUCTION

In modern communication systems, it is expected that together with narrow band information, high-speed data and video will also be integrated in a common network. Optical transmission and switching systems are expected to be widely used in such a network. And play an important role in realizing the broadband, bit-rate independent future communication systems. Moreover, the optical switches are the basic vital element of modules like switch fabric, Optical Cross connect (OXC), Optical Add Drop Multiplexer (OADM), Wavelength Converters (WC).

Hence, sufficient effort must be shown to get suitable switch elements in order to meet the above said requirements.

At switching times below of the order of $10^{-11}$ s, Photonic is the technology of the choice. In the region of $10^{-11}$ to $10^{-15}$ s, integrated optic devices are often used, with electrical control, to route light from one path to other. Recent years have seen a dramatic improvement in the size and speed of electronic devices, the exponential pace of microelectronics is well known. When reduced to nanometer scales, current switches may not be the best way to code information. The developing technology of quantum dot fabrication may prove a key element in crafting another approach.

Although, solutions can be obtained through non-linear phenomena in optical domain by realizing optical devices, they have their own drawbacks. Alternatively, with quantum dots, devices like optical sources, modulators, detectors etc., have been started to design and very soon will be made available in the market.

This paper employs the circuit model approach to analyze the optical switch and fabric based on quantum dot structures. For this analysis 2X2 TIR switch and 4X4 Spanke switch fabric have been taken as switch element and fabric respectively. The InAs of 100 A’ diameter grown electrochemically on gold substrate of [1] has been considered as quantum dot structure. The necessary data with respect to quantum dot are taken from [1,2]. The speed of the device is calculated based on the relation given in [3]. The equivalent circuit for TIR QD is derived from [4].

TIR switch had been fabricated by Tsai et al. by Ti diffusion of Y cut LiNbO₃ bulk semiconductor. In this paper, if it is by QD, what is the switching time, associated impedance and insertion loss. Then having such a type as the basic switch element, if
fabric like Spanke switch configuration is realized, what is the switching speed, impedance and insertion loss are calculated with the help of Saber sketch simulator and equivalent model approach.

2. OPTICAL SWITCH

Any communication system is incomplete if one does not have proper switching devices to either route the information carrying signals or to control the communication system itself. In fiber optic communication, switching can be implemented in the electronic domain. However, a more elegant way would be to use a Photonic switch, which handles the signal in the optical domain. But in this switch, electro-optic principle is the principal concept of the subject.

2.1 Quantum dot structure

The schematic to realize QD structure is shown in Figure 1. But it is not a layered structure as like MQW and QWR. In QD the electron states all three possible directions (x, y, z) are quantized and confined. In QDs, the electrons and holes behave in a zero-dimensional fashion. The resultant structure is called quantum dot or quantum box. As a result of the strong confinement imposed in all three spatial dimensions QD systems are similar to atoms and therefore frequently referred to as artificial atoms, super atoms. Due to this confinement the electronic properties of QD depends on their size in the nanometer regime.

![Figure 1: Schematic of QD Structure](image)

The dots can be grown electrochemically on the substrate leading to dot/substrate barrier [5] with a relatively high capacitance. Alternatively, colloidal nano crystals can be linked to the substrate by organic spacer molecules resulting in a dot/substrate barrier with a relatively low capacitance as shown Figure 2. Optical absorption and photoluminescence were first used to study the electronic structure of nanometer-sized semiconductor, colloids. In latter, scanning probe techniques such as scanning tunneling spectroscopy (STS) and scanning near field optical microscopy (SNOM) are used to analyze electrical and optical measurements on individual particles can be performed.

![Figure 2: Schematic representation of a QD that has been chemically attached to a gold substrate](image)

2.2 Analysis of QD structure

To analyze, the structure of Figure 2 has been taken. The InAs QD of 100Å diameter is grown on electrochemically on gold substrate. The capacitance of .25 aF is calculated by assuming \( \varepsilon_r = 14.6 \) for InAs [3] and the distance is 40 nm [5]. Then simulation is done, Figure 3 shows the response of QD structure. The bandwidth of \( 12.503 \times 10^{15} \) is obtained. The calculated switching time is 0.5 fs.

![Figure 3: Response of QD Structure](image)
2.3 QD structured TIR electro-optic switch (2x2)

The schematic diagram of QD structured TIR (2X2) electro-optic switch [6] is shown in Figure 4. There are four horn-shaped tapered channel wave guides form the input and output ports to the switch which contains a region in which the refractive index can be reduced by the application of electric field in the electrode. The QDs are arranged between two metal plates which act as electrodes as shown in Figure 4. The bonding wires have been taken to apply electric field.

If there is no applied voltage, an incident light beam from, for example port 1 will encounter no index change at interface and will pass free to port 4 (not shown in Figure). However a voltage is applied with the proper polarity to reduce the refractive index between the electrodes, TIR may occur, thereby causing partial (or possible total) switching of the light beam to port 3 (not shown in Figure).

![Figure 4: Schematic of QD Structured electro-optic Switch (2X2)](image)

2.4 Equivalent circuit model

The equivalent circuit for TIR QD structured switch is derived from [4]. The circuit is obtained by considering single quantum dot (SQD) is kept between the electrodes. Figure 5 shows a lumped circuit model for a InAs QD total internal reflection electro-optic switch. The diameter of the dot is 100Å. \( L_w \) is the bonding wire inductance, which is assumed to be 0.001nH. The bonding wire resistance is negligible \( R_s \) is the source resistance, the value is 50Ω. \( C_1 \) and \( C_2 \) are the capacitances between QD and top electrode, QD and bottom electrodes respectively and the top electrode. \( R_1 \) and \( R_2 \) are the resistances between top electrode and QD, bottom electrode and QD respectively which are assumed to be 10KΩ.

![Figure 5: Circuit model of InAs SQD TIR electro-optic switch](image)

The values of \( C_1 \) and \( C_2 \) are calculated by

\[
C_1 = \frac{\hat{\alpha}_0 \hat{A}}{d_1} \tag{1}
\]

\[
C_2 = \frac{\hat{\alpha}_0 \hat{A}}{d_2} \tag{2}
\]

\( d_1 \) is the distance between QD and top electrode, assumed to be 200nm. \( d_2 \) is the distance between QD and bottom electrode, assumed to be 40nm.

![Figure 6: Response of TIR Electro-optic switch](image)

Figure 6 shows the response of TIR switch in SQD structure. The bandwidth of 2.195x10^{15} Hz is obtained. The switching time of the switch is 2.86fs.
3. SPANKE NETWORK

The spanke architecture [7] is shown in Figure 7 turning out to be a popular architecture for building large nonintegrated switches. An n x n switch is made by combining n 1 x n switches along with n n x 1 switch. The architecture is strict—sense nonblocking, requires 2n (n-1) 1 x 2 switches and each path has length 2 log2n. In spanke architecture the signal has to travel with only four switch elements to reach any output port. So the response of the circuit model has been analyzed by cascading the switch elements and tabulated in Table 1.

![Figure 7: Spanke switch configuration](image)

3.1 Equivalent circuit of QD structure spanke network and analysis

The equivalent circuit of spanke network (4X4) based on QD structured TIR electro-optic switch element is shown in the Figure 8.

![Figure 8: Equivalent circuit of QD structured spanke network](image)

The equivalent circuit is obtained by assuming only one input port is enabled at a time. The parasitic capacitance and resistance while coupling switch elements are ignored. So the resultant is the cascaded form of single switch elements’ circuit as shown in Figure. Using saber simulator the switching time for different cascaded switch elements is obtained and summarized in Table 1.

<table>
<thead>
<tr>
<th>No. of switch elements cascaded</th>
<th>Band width T Hz</th>
<th>Switching Time Fs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.1954</td>
<td>2.86</td>
</tr>
<tr>
<td>2</td>
<td>747.28</td>
<td>8.40</td>
</tr>
<tr>
<td>3</td>
<td>390.85</td>
<td>16.07</td>
</tr>
<tr>
<td>4</td>
<td>275.00</td>
<td>22.85</td>
</tr>
<tr>
<td>5</td>
<td>195.88</td>
<td>32.07</td>
</tr>
<tr>
<td>6</td>
<td>164.56</td>
<td>38.18</td>
</tr>
<tr>
<td>7</td>
<td>148.70</td>
<td>42.25</td>
</tr>
</tbody>
</table>

Table 1 shows the variation of switching time for cascading QD structured TIR electro-optic switch elements. Figure 9 shows the response of switching time of cascading switch elements against number of switch elements. The switching time decreases if the number of cascaded switch element increases. The switching time of spanke network is 22.85fs for 100A\(^0\) InAs QD.

![Figure 9: Switching time vs. Number of switch elements cascaded](image)

4. INSERTION LOSS

Insertion loss is the very important parameter for any switch element. It is defined to be the ratio of the optical power at the output of the device to the power at the input, when the device is biased at maximum transmission.

\[
L_i = 1 - \frac{P_o}{P_{in}} \tag{3}
\]

where
- \(P_o\) Output optical power at the off state of the applied voltage.
- \(P_{in}\) Input optical power.
Otherwise, the amount of power dissipation in dB of the given system is also said to be insertion loss. The amount power dissipation is calculated by calculating the loop impedance of the switch and in turn the current flow, then the power dissipated by the switch is given by

\[ P_{\text{diss}} = I^2 Z \] (4)

![Figure 10: Circuit to calculate the Impedance](image)

The circuit shown in Figure 11 is used to obtain the loop impedance and the operating frequency has been taken from the TIR switch response shown in Figure 6.

To calculate the insertion loss of a spanke network, first the impedance of the spanke network is obtained. (by cascading this circuit shown in Figure 10 to four stages, and calculating the loop impedance) Then the current flowing through the spanke network is calculated.

5. RESULTS

The following results are obtained for optical switch and switch fabric.

<table>
<thead>
<tr>
<th>Band Width</th>
<th>Switching Time</th>
<th>Impedance</th>
<th>Current</th>
<th>Insertion loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switch</td>
<td>2.2 THz</td>
<td>2.86 fs</td>
<td>12.5 KΩ</td>
<td>79.37 nA</td>
</tr>
<tr>
<td>Fabric</td>
<td>275 THz</td>
<td>22.85 fs</td>
<td>16.0 KΩ</td>
<td>62.26 nA</td>
</tr>
</tbody>
</table>

6. CONCLUSION

Interest in high performance optical switches has increased recently because of increased performance demands of system that use them. In this paper optical switch of TIR switch has been analyzed in quantum structure. Their performances in Spanke network have been also discussed. The obtained results indicate that these switches are quite better than other non-all-optical switches and comparable with all-optical switch responses.

7. REFERENCES


