Performance analysis of all optical time division multiplexed router based on terahertz optical asymmetric demultiplexer

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ABSTRACT

Growing demands for bandwidth have stimulated the development of high-speed optical shared media networks. At present, most research on optical networking has concentrated on wavelength-division multiplexing (WDM). Optical time-division multiplexing (OTDM) is considered as an alternative to WDM offering data rates greater than 100 Gb/s using just a single wavelength. In such systems all optical routers, which overcomes the bottleneck of optoelectronic conversion, play an important role. This paper investigates TOAD based 1 x 4 optical router by developing a mathematical model. The proposed model is simulated and results for crosstalk are presented and compared with 1 x 2 router.

Keywords: Optical communication system, Optical switches, routers, demultiplexing, Optical Time division multiplexing, terahertz optical asymmetric demultiplexer, optical signal processing.

1. INTRODUCTION

The growing demand for increased network capacity has generated interest in the development of ultrafast transparent optical networks (TONs). In these networks, the tardy opto-electrical (O/E) or electro-optical (E/O) conversions that are inherent in current fibre network systems are avoided. Consequently, there is a significant reduction in bandwidth bottlenecks resulting in superior quality of service (QoS)\textsuperscript{1}. To date most research on optical networking has concentrated on WDM, which routes different packets according to the wavelength of the optical carrier. Optical time-division multiplexing is considered as an alternative to WDM for future networks, which utilise a single wavelength for high (> 100 Gbit/s) data rates\textsuperscript{2,3}. In OTDM networks many signals are interleaved before being transmitted using a single wavelength. Each signal from a lower bit-rate source is broken up into many segments (slots), each having very short duration, and are multiplexed in a rotating repeating sequence (i.e. round robin fashion) onto a high bit-rate transmission line. The use of short duration pulses (preferably soliton) allows information to be transmitted at very high bit rates (>100 Gb/s). An asset of OTDM is its flexibility, which allows for variation in the number of signals that can be transmitted over a single fibre, and the ability to adjust the time intervals to make optimum use of the available bandwidth. It is therefore believed that OTDM networks are excellent candidates for meeting the future ultrafast network requirements\textsuperscript{5,7}.

In order to realise high-speed OTDM systems, many technologies have been proposed, including ultrashort optical pulse generation, time division multiplexing, optical repeaters, synchronisation and time domain demultiplexing.

Here we investigate 1 x 4 optical router based on the terahertz optical asymmetric demultiplexer (TOAD) by developing a mathematical model. The router operation is based around TOAD, which is used in two distinct modes (i) a bit level demultiplexer for the header, and (ii) a frame level demultiplexer for the payload. As a result less stringent requirements are need with regard to the TOAD switching resolution for payload extraction than header extraction. The incoming OTDM packet is composed of a header and payload information. The header information is extracted using the first TOAD, which is then used to make a routing decision for the payload information. The payload information is routed through a second TOAD according to the information contained in the header. The proposed model is simulated using

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dedicated simulation software, for a case where the packet bit period is 4ps, which corresponding to a 0.25 Tb/s optical network. Crosstalk performance is investigated and the results are compared with 1 x 2 router.

2 MATHEMATICAL MODEL

The schematic diagram of the 1 x 4 router is shown in Fig. 1. Each 1 x 2 router is composed of two TOAD switches with two outputs to realise single input multi-output switching. The operation principle follows the same concept as 1 x 2 router, which can be found in [9].

![Schematic diagram of 1 x 4 router](image)

The switching equation for the router A is given as:

\[
\begin{pmatrix}
E_1 \\
E_2
\end{pmatrix} = (1 - \gamma)e^{-\alpha L} \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \begin{pmatrix} E_{in} \\ 0 \end{pmatrix},
\]

(1)

The coefficients are given as:

\[
\begin{align*}
a_{11} &= ke^{i(\phi_{cw})} G_{cw} + ke^{i(\phi_{ccw}+\pi)} G_{ccw} \\
a_{12} &= ke^{i(\phi_{cw}+\pi/2)} G_{cw} + ke^{i(\phi_{ccw}+\pi/2)} G_{ccw} \\
a_{21} &= ke^{i(\phi_{cw}+\pi/2)} G_{cw} + ke^{i(\phi_{ccw}+\pi/2)} G_{ccw} \\
a_{22} &= ke^{i(\phi_{cw}+\pi)} G_{cw} + ke^{i(\phi_{ccw})} G_{ccw}
\end{align*}
\]

where \(G_{cw}\) and \(G_{ccw}\) are the gains of SLA for clockwise and count-clockwise components in TOAD, respectively, \(\gamma\) is the coupler excess loss, \(\alpha\) is the fiber loss, and \(L\) is length of fibre loop.

Here it is assume that both the excess loss of the coupler and the fiber loss is equal to zero for short fiber length.

The outputs of 1 x 2 routers B and C are given as, respectively:
\[
\begin{align*}
\begin{pmatrix}
E_3 \\
E_4
\end{pmatrix} &= \begin{pmatrix}
a_{11} & a_{12} \\
a_{21} & a_{22}
\end{pmatrix} \begin{pmatrix}
E_1 \\
0
\end{pmatrix}, \\
\begin{pmatrix}
E_5 \\
E_6
\end{pmatrix} &= \begin{pmatrix}
a_{11} & a_{12} \\
a_{21} & a_{22}
\end{pmatrix} \begin{pmatrix}
E_2 \\
0
\end{pmatrix}.
\end{align*}
\]

Equations (2) and (3) are substituted into (1) giving:

\[
\begin{align*}
\begin{pmatrix}
E_3 \\
E_4
\end{pmatrix} &= \begin{pmatrix}
a_{11} & a_{12} \\
a_{21} & a_{22}
\end{pmatrix} \begin{pmatrix}
a_{11} E_{in} \\
0
\end{pmatrix}, \\
\begin{pmatrix}
E_5 \\
E_6
\end{pmatrix} &= \begin{pmatrix}
a_{11} & a_{12} \\
a_{21} & a_{22}
\end{pmatrix} \begin{pmatrix}
a_{21} E_{in} \\
0
\end{pmatrix},
\end{align*}
\]

The output of the 1 x 4 may be expressed as:

\[
\begin{align*}
\begin{pmatrix}
E_3 \\
E_4 \\
E_5 \\
E_6
\end{pmatrix} &= \begin{pmatrix}
a_{11}a_{11} & a_{11}a_{12} \\
a_{11}a_{21} & a_{11}a_{22} \\
a_{21}a_{11} & a_{21}a_{12} \\
a_{21}a_{21} & a_{21}a_{22}
\end{pmatrix} \begin{pmatrix}
E_{in} \\
0
\end{pmatrix},
\end{align*}
\]

where

\[
\begin{align*}
B_{11} &= a_{11} \ast a_{11} = k^2 e^{j(2\phi_{cw})} G_{cw}^2 + k^2 e^{j(2\phi_{cw}+\pi)/2} G_{ccw}^2 + k^2 e^{j(2\phi_{cw}+2\phi_{ccw}+2\pi)} G_{ccw} G_{cw} \\
B_{12} &= a_{11} \ast a_{12} = k^2 e^{j(2\phi_{cw}+\pi)/2} G_{cw}^2 + k^2 e^{j(2\phi_{cw}+3\pi/2)} G_{ccw}^2 + k^2 e^{j(2\phi_{cw}+2\phi_{ccw}+2\pi)} G_{ccw} G_{cw} \\
B_{21} &= a_{11} \ast a_{21} = k^2 e^{j(2\phi_{cw}+\pi)/2} G_{cw}^2 + k^2 e^{j(2\phi_{cw}+3\pi/2)} G_{ccw}^2 + k^2 e^{j(2\phi_{cw}+2\phi_{ccw}+2\pi)} G_{ccw} G_{cw} \\
B_{22} &= a_{11} \ast a_{22} = k^2 e^{j(2\phi_{cw}+\pi)} G_{cw}^2 + k^2 e^{j(2\phi_{cw}+\pi+\pi)} G_{ccw}^2 + k^2 e^{j(2\phi_{cw}+2\phi_{ccw}+2\pi)} G_{ccw} G_{cw} \\
B_{31} &= a_{21} \ast a_{11} = k^2 e^{j(2\phi_{cw}+3\pi/2)} G_{cw}^2 + k^2 e^{j(2\phi_{cw}+3\pi/2)} G_{ccw}^2 + k^2 e^{j(2\phi_{cw}+2\phi_{ccw}+2\pi)} G_{ccw} G_{cw} \\
B_{32} &= a_{21} \ast a_{12} = k^2 e^{j(2\phi_{cw}+\pi)} G_{cw}^2 + k^2 e^{j(2\phi_{cw}+\pi+\pi)} G_{ccw}^2 + k^2 e^{j(2\phi_{cw}+2\phi_{ccw}+2\pi)} G_{ccw} G_{cw} \\
B_{41} &= a_{21} \ast a_{21} = k^2 e^{j(2\phi_{cw}+\pi+\pi)} G_{cw}^2 + k^2 e^{j(2\phi_{cw}+\pi+\pi)} G_{ccw}^2 \\
B_{42} &= a_{21} \ast a_{22} = k^2 e^{j(2\phi_{cw}+3\pi/2)} G_{cw}^2 + k^2 e^{j(2\phi_{cw}+3\pi/2)} G_{ccw}^2.
\end{align*}
\]
3. SIMULATION OF THE ALL OPTICAL ROUTER

Figure 2 shows the format of two consecutive packets used in the simulation. Framing bits indicate the inter-packet boundaries thereby providing a synchronisation mechanism. The two address bits indicate the destination port to which the payload information is routed. A value of ‘0’ (‘1’) results in the payload information being reflected (transmitted) during each stage.

<table>
<thead>
<tr>
<th>Frame Sync.</th>
<th>Address (00/11)</th>
<th>Payload information (1101...01)</th>
<th>Frame Sync.</th>
<th>Address (00/11)</th>
<th>Payload information (0110...10)</th>
</tr>
</thead>
</table>

Fig. 2: Format of OTDM packet signal.

Equation 7 is used to simulate the output of the 1 x 4 router. The model used for TOADs is the same as that given in [9], and the parameters used are given in Table 1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K$</td>
<td>0.5</td>
</tr>
<tr>
<td>Control pulse width FWHM</td>
<td>2 ps</td>
</tr>
<tr>
<td>Control pulse wavelength</td>
<td>1500 nm</td>
</tr>
<tr>
<td>Control pulse power</td>
<td>0.8 pJ</td>
</tr>
<tr>
<td>Control pulse period</td>
<td>100 ps</td>
</tr>
<tr>
<td>Data signal width FWHM</td>
<td>2 ps</td>
</tr>
<tr>
<td>Data signal wavelength</td>
<td>1550 nm</td>
</tr>
<tr>
<td>Data frame time</td>
<td>100 ps</td>
</tr>
<tr>
<td>SLA length</td>
<td>300 µm</td>
</tr>
<tr>
<td>Number of SLA</td>
<td>200</td>
</tr>
<tr>
<td>SLA active area</td>
<td>$0.2e^{-12}$ m$^2$</td>
</tr>
<tr>
<td>SLA carrier lifetime</td>
<td>300 ps</td>
</tr>
<tr>
<td>SLA transparent carrier density</td>
<td>$10^{24}$ m$^{-3}$</td>
</tr>
<tr>
<td>SLA confinement factor</td>
<td>0.3</td>
</tr>
<tr>
<td>SLA position $\Delta x$</td>
<td>2 ps</td>
</tr>
</tbody>
</table>

Table 1 Simulation parameters.

Figure 3 shows the waveforms at the input and output ports of the 1 x 4 router. The three packets used at the input are 21100, 21000, and 20100. Observe that the packet consists of a frame signal, distinguishable by its higher amplitude, two bit addresses and payload information. According to the routing convention established earlier, packets 1, 2 and 3 are routed to ports 3, 4 and 5, respectively. Also present are small amount of inter-packet crosstalk due to inter-channel crosstalk and residual crosstalk associated with TOADs.
4 SIMULATION RESULT

4.1 Crosstalks vs. Bit Rate

The overall crosstalk is composed of inter-channel crosstalk and residual crosstalk. The former is caused by the non-target channels appearing within the switching window, whereas the latter is due to the counter propagation of clockwise and counter-clockwise components. The crosstalk increases with the data rate. This is because of an increase in the number of bits appearing within the switching window whose width is kept constant. Using the parameters shown in Table 1, the crosstalk at the output node was simulated using equation (7), and the results over a range of OTDM bit rate are shown in Fig. 4. The crosstalk increases with the bit rate reaching $-11.97\text{dB}$ at $200\text{Gb/s}$. Comparing this result with that of $1 \times 2$ optical router, the crosstalk increases by about $4\text{ dB}$. This is due to an increase in the number of TOADs in $1 \times 4$ router.

![Packet waveforms at the input and outputs of the 1 x 4 router.](image-url)
4.2 Crosstalk vs. Control Pulse Energy

The width of switching window is determined by the position of the SLA within the loop. By placing the SLA asymmetrically, one can reduce the time resolution to a value far less than the recovery time of the optical non-linearity. In a loop with small asymmetry a strong slow non-linearity associated with the SLA can facilitate ultrafast all optical switching, thus avoiding the need for optoelectronic conversion. The control pulses induces the non-linearity of the SLA, which determined the output profile of the router.

The crosstalk with different control pulse energy was simulated using (7), and the results are shown in Fig. 5. It can be
seen that the crosstalk is relatively low (about 19.5 dB) at control pulse energy < 0.2 pJ. This is because the control pulse energy is not sufficient enough to induce SLA non-linearity. Thus, signals, after propagating through the loop, are reflected back to the input port of the TOAD. The crosstalk is at its peak value of -14.4 dB when the control pulse energy is 0.2 pJ, decreasing to -15 dB at control pulse energy of 1.9 pJ. The reason for sudden increase in the crosstalk is because the control pulse energy affects the carrier density of the SLA, which determines the gain of the switching window. In other words, the more power, the more gain within the region of 0.2 pJ to 1.9 pJ. The simulation results are in good agreement with the experimental results\(^8\). We have shown that it is possible to route OTDM packet signals at 200Gbit/s with switching energy of 0.2 pJ or more, assuming that the data signal energy is 0.1 pJ and there is no influence of the data signal on the carrier density among other things.

5 CONCLUSION

A comprehensive study of a mathematical model of an all optical 1 x 4 router based on TOAD is presented. Dedicated simulation software is used to implement the model. The model can recognise the address bits and route packet signals for a case where the packet bit period is only 4ps, which corresponds to a 0.25 Tb/s bandwidth optical network. Crosstalk performance is investigated and the results are compared to 1 x 2 router. It is shown that there is a trade off between crosstalk and data rate. Results also show that there is an optimum switching energy of 0.2 pJ beyond which the crosstalk will decrease by about 0.5 dB and below which there will be no switching at all. Finally, we believe that the proposed router, which overcomes the bottleneck of optoelectronic conversion, has potentially useful characteristics as a component for high-speed all optical TDM networks due to its ultrafast switching capability. Further work will investigate network with multiple inputs and outputs.

REFERENCE


