BER Performance Analysis of 100 and 200 ~~Gb/s~~Gbps All-optical OTDM Node Using Symmetric Mach-Zehnder Switches

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Abstract:

In future high-speed self-routing photonic networks based on ~~all optical~~all-optical time division multiplexing~~ed~~ (OTDM) it is highly desirable to carry out packet switching, clock recovery and demultplexing in the optical domain in order to avoid the bottleneck due to the optoelectronics conversion. In this paper we propose a self-routing OTDM node structure composed of an all-optical router and a demultiplexer based on the symmetric Mach-Zehnder (SMZ) for high bit rate OTDM packets. Here, we investigate both numerically and by means of simulation the ~~SMZ~~ noise and crosstalk characteristics of the SMZ and the bit error rate (BER) performance of the proposed OTDM node. For BER of 10^{-9} and the total bit rates of 100 and 200 ~~Gb/s~~Gbps the power penalty incurred are about 2 and 2.5 dB, respectively compared with 2.5 Gbps back-to-back (B-B) system.

1. Introduction

The future communication systems will rely on the 3rd generation all-optical network to address the growing demand for capacity. Packet switching systems based on the dense wavelength division multiplexing (DWDM) and OTDM or combination of both technologies are capable of fully realising the ultra-high speed optical networks. DWDM is widely used offering capacity in excess of 160 ~~Gb/s~~Gbps using many wavelengths. OTDM is capable of transporting hundreds of ~~Gb/s~~Gbps in the form of bit or packet interleaving format, and using only a single wavelength, which has attracted much attention in the last few years. At a very high speed it is highly desirable to carry out the entire signal routing, switching, demultiplexing and processing in the optical domain in order to avoid bottleneck due to the optical-to-electronic conversion.

A packet is normally composed of the address bits and the payload (information bits). Multiplexing of the clock signal (CS) with each packet can be carried out in a number of ways such as: space division multiplexing (SDM), WDM, orthogonal polarization, intensity division multiplexing and time division multiplexing [1]. In SDM, the optical clock signal and payload are carried on separate fibres. Although this scheme is the simplest to implement, ~~but~~ it has ~~there are~~ two main drawbacks: ~~-~~ (i) t~~T~~he time varying differential delay between the clock and data signals due to temperature variation, which~~that~~ may affect fibres unequally, and (ii) high installation cost. In WDM scheme~~s~~, ~~D~~different wavelengths are allocated to CS and payload ~~in WDM scheme~~ [2]. This technique is only practical for predetermined path lengths between nodes in single hop networks such as point-to-point links or broadcast-and-select star networks. In a non-deterministic optical path length for asynchronous packet switching scheme, ~~Since the optical path length through which a packet travels is non-deterministic, then~~ ~~T~~the relative delay between the CS and payload will be ~~random~~ stochastic~~in asynchronous packet-switched~~ ~~since the optical path length through which a packet travels is non-deterministic~~. Orthogonally~~-~~ polarized clock synchronization schemes are more suitable for small size networks [3], whereas in larger networks correct polarization maintenance throughout the network is rather difficult ~~to maintain~~ due to the fibre polarization mode dispersion and other non-linear effects. Although synchronization based on transmission of high intensity optical CS offers simplicity, ~~but~~ maintaining the clock position and its intensity level over a long transmission span is a problem due to the impact of fibre non-linearities [4]. Multiplexing of the CS in time domain with the same intensity and wavelength~~,~~ as the data signal is the preferred option ~~that~~, which ~~has been~~is adopted in this work.

All~~-~~optical switches based on the cross-phase modulation (XPM) in conjunction with interferometric configurations such as Mach-Zehnder interferometer (MZI), terahertz optical asymmetric demultiplexer (TOAD) and ultrafast nonlinear interferometer (UNI) could be used as the building block for both the router and demultiplexer [1],[5]. TOAD~~-~~based switches ~~is~~ are composed of a short fibre loop and a nonlinear element (NLE) placed asymmetrically off the centre point of the loop. ~~s that the d~~Demultiplexing function is achieved solely by means of phase modulation. With the NLE being off-centred, an asymmetrical switching window (SW) profile is obtained~~,~~ due to the counter-propagating nature of the control pulse (CP) ~~signal~~ against the data pulse~~signal~~ within the loop. These characteristics of the ~~TOAD~~ TOAD-based switches result in an increased crosstalk (CXT) and noise. The SW of the UNI is determined by the birefringence of the fibre used to separate the orthogonally-polarized components of the data pulses in time domain [6]. The main drawback of the UNI switch is its poor integrate-ability, since it requires at least 15 m of birefringent fibre to ~~produce~~ achieve the switching process [7]. Furthermore the switch ~~should~~needs to ~~must~~ maintain and control the ~~employ extensive~~ polarization ~~control~~ to ensure ~~maintain~~ reliability, which adds to the cost and complexity of the switch ~~. Polarization maintaining components and polarization control devices increase the cost of the switch~~ [8].

Among these interferometric configurations, the monolithically integrated MZI switches are the most promising due to their compact size, thermal stability, symmetrical SW profile, and low-~~-~~power operation. ~~All optical~~All-optical demultiplexing employing MZI switches at 160 ~~Gb/s~~Gbps or above has been reported in [9] ~~,~~and [10]. Considering various MZI configurations, the SMZ structure provides the highest flexibility and narrowest SW with symmetrical profile [11][12]. Recently, for the first time, we reported an all-optical clock recovery module and a 1×2 OTDM router employing SMZs [11]. A 1× 2 router based on TOADs has been proposed for all-optical address recognition and single bit self-routing in a Banyan-type network [13]. However, the orthogonally-polarized CS used in the router is rather difficult to maintain due to the polariz~~s~~ation-mode dispersion inherent in the optical fibre link. This problem can be avoided by using packets with signals that have ~~signals in the packet with~~ identical polariz~~s~~ation, intensity, pulse width and wavelength.

In this paper we propose an all optical OTDM node structure composed of a router, a demultiplexer based on the SMZ, optical pre-amplifier and optical receiver for 100 and 200 ~~Gb/s~~Gbps and investigated its BER performance. Theoretical investigation of the BER performance of OTDM systems employing an all-optical demultiplexer and an optical receiver has been studied in [14] and [15]. However no work has been reported on the BER performance of an OTDM node employing SMZ-based all-optical router and demultiplexer, optical pre-amplifier and optical receiver. Here for the first time we show an OTDM node structure where packet routing and channel demultiplexing is carried out in all-optical domain. Since practical evaluation of the BER performance of the proposed scheme requires complex and costly test bed, ~~here~~ we have used a dedicated simulation package to carry out detailed simulation and evaluation of the proposed OTDM node. Predicted BER performance is compared with the simulation results, which in turn are assessed against a 2.5 ~~Gb/s~~Gbps B-B system. The structure of this paper is as follows. The operation principles of the SMZ switch, ~~and~~ the noise and crosstalk characteristics of the switch and the BER analysis are outlined in section 2.

Simulation model and results are presented in Section 3. Finally, in Section 4, the concluding remarks are given.

2.0 Theory

Figure 1 shows a block diagram of a complete proposed OTDM system which comprises ~~composed of~~an OTDM multiplexer, a long length of fibre (30 km) with in-line amplifiers and dispersion compensated fibre (5.4 km), the clock and address bits extraction modules, a 1 × *M* optical switch, an optical delay lines, an optical demultiplexer, an optical pre-amplifier, an optical filter and a conventional optical receiver. The OTDM transmitter is composed of a single continuous-wave laser source at wavelength of 1550 nm, M-Z external modulators, and a number of optical delay lines for composing the OTDM packet. OTDM packet is composed of a clock bit, two address bits and payload (8-channels), and a packet guard band. The CS could be at different wavelengths [16], polariz~~s~~ations [17], bit rates [18], or intensities [14] in comparison with the remaining signals within the packets. In the SMZ based switches ~~control pulses (~~CPs~~)~~ with different wavelength to that of the data pulses have been reported in [6] and ~~-~~[7]. However, these schemes have a number of drawbacks such as: the generation and transmission of packets are significantly complicated, and the clock pulses may lose their timing relation with respect to other pulses in the same packets after propagating over a long distance [15]. Here all the components (clock, address and the payloads) in the packet have the same polariz~~s~~ation, pulse intensity and width, and wavelength. At the node, the CS extracted from the received OTDM packet using two in~~-~~line SMZs which will be~~is~~ used as the CP~~control signal~~ for address extraction and demultiplexer modules. The extracted address bits are used as the CP in the 1 × *M* optical switch to route the entire delayed OTDM packet to one of its output ports. Detail operation of the router can be found in [11] and [19]. The switched OTDM packet will then ~~is~~ pass~~ed~~ through the demultiplexer in order to extract a single channel from the OTDM payload. The single demultiplexed ~~single~~ channel is ~~passed through~~then amplified and bandlimited via an optical pre-amplifier and an optical band-pass filter respectively, before being processed by the optical receiver to recover the original 2.5 Gbps data stream. The receiver unit consists of an ideal PIN photodetector, an amplifier, a sixth order electrical low-pass Bessel filter, a sampler and a threshold level detector.

2.1 SMZ switching window

The semiconductor optical amplifier (SOA) is the fundamental building block for the majority of optical switches because of its high extinction ratio, low cost and easy integration with other devices. Figure 2 shows the block diagram of a typical SMZ switch composed of two identical SOAs, positioned in the same locations on each arm of the interferometer, and a number of 3-dB couplers. The operation principle is based on the optically induced refractive index change within the SOA'~~s~~ through appropriately synchronised optical CP trains that alter the phase conditions of data signals in the interferometer, thus ~~causing~~ resulting in switching. Control and data signals, with orthogonal polariz~~s~~ation, are fed into the switch via 3-dB couplers and co-propagate within the switch. In the absence of CPs, the data signals entering the switch via a coupler (C_1) splits into two equal intensity signals with 90° phase shift, $E_1(0)$ and $E_2(\pi/2)$, which ~~propagating~~ propagate along the upper and lower arms of the interferometer, respectively. Couplers C_2 and C_3~~,~~ are in the bar state for data signal therefore, introducing~~e~~ no additional phase shift $\Delta\phi$ in the interferometer. With no CP present E_1 and E_2 will experience the same relative $\Delta\phi$ during propagation and ~~recombining~~ recombine at the output of C_4. The data signals at the output ports (O/P) 1 and 2 are given as:

$$E_{out,1} = E_{out}^{UA}(0) + E_{out}^{LA}(\pi) \qquad (1)$$

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$$E_{out,2} = E_{out}^{UA}(\pi/2) + E_{out}^{LA}(\pi/2) \qquad (2)$$

$$\cancel{E_{out,1} = E_{out}^{UA}(0) + E_{out}^{LA}(\pi)\,,} \qquad \cancel{(1)}$$

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$$\cancel{E_{out,2} = E_{out}^{UA}(\pi/2) + E_{out}^{LA}(\pi/2)\,,} \qquad \cancel{(2)}$$

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where E_{out}^{UA} and E_{out}^{LA} are the signals at the output of the SOA in the upper and lower arms of the interferometer, respectively. Note that from (1), there is ~~that~~ no signals ~~will emerge~~ emerging from the O/P1. However, with CPs present $\Delta\phi$ is introduced between the two arms of the interferometer, thus causing the data signals to be switched to the O/P1, see Fig. 2. To achieve a complete switching at $\Delta\phi = \pi$, CP1 enters the interferometer via C_2 just before the target data signal. The CP will then saturate ~~the~~ SOA1, thus changing its gain as well as its phase characteristics. When ~~Propagating~~ the data signal ~~entering~~ enters the interferometer following the CP1, it will experience a different $\Delta\phi$ (i.e. π) in the upper arm relative to the lower arm. The data signal emerging from the O/P1 is given as:

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$$E_{out,1} = E_{out}^{UA}(\pi) + E_{out}^{LA}(\pi)\,. \qquad (3)$$

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No signal will emerges from the O/P2 since E_1 and E_2 components will cancel each other, see Fig. 2. Introducing the second CP2, delayed by T_{delay} with respect to CP1, just after the data signal, into the interferometer via C_3 will saturate ~~the~~ SOA2, thus resulting in the same $\Delta\phi$ as in the upper arm, thereby resetting the switch. Therefore, with this mechanism the SMZ switch-on-and-off time is controlled by fast optical excitation process ~~hence~~ which overcome the slow relaxation time ~~can be overcome~~. Note that T_{delay} determines the SMZ nominal width of the SW. An optical polarization beam splitter (PBS) is used ~~To~~ to separate the data and control signals at the output port of the SMZ ~~an optical polarizsation beam splitter (PBS) is used~~. Practical switches and 3-dB couplers would normally have a small amount of net loss, ~~and~~ which can be compensated by the gain of the SOAs. If necessary an additional amplifier could be incorporated at the output of the SMZ, but this will introduce additional noise.

The electric fields at the O/P~~s~~ 1 and O/P2 of the SMZ, ~~defined~~ in terms of the relative gain G and phase ϕ of the incident fields within the upper and lower arms can be expressed as:

$$\begin{pmatrix} E_{out,1}(t) \\ E_{out,2}(t) \end{pmatrix} = \begin{pmatrix} (1-\alpha)^{1/2} & j\alpha^{1/2} \\ j\alpha^{1/2} & (1-\alpha)^{1/2} \end{pmatrix} \begin{pmatrix} E_{2,in}^{UA}(t) G_1(t) e^{-j\phi} \\ E_{1,in}^{LA}(t) G_2(t) e^{-j\phi} \end{pmatrix}, \qquad (4)$$

where α is the coupling factor. Note, $E_1 = E_2 = 0.5E_{in}$. Equation 4 can be expanded as:

$$E_{out,1}(t) = E_{in}(t)\left[(1-\alpha)^{3/2} G_1 - \alpha(1-\alpha)^{1/2} G_2\right], \qquad (5)$$

$$E_{out,2}(t) = jE_{in}(t)\left[\alpha^{1/2}(1-\alpha)G_1 + \alpha^{1/2}(1-\alpha)G_2\right]. \qquad (6)$$

Here a coupling ratio α of 0.5 is adopted that results in $\left|E_{1,in}^{UA}(t)\right| = \left|E_{1,in}^{LA}(t)\right|$ and $\pi/2$ relative phase difference. Consequently, the signal powers at the output of the SMZ are given as:

$$P_{out,1}(t) = 0.125 P_{in}(t) \cdot \left[G_1(t) + G_2(t) - 2\sqrt{G_1(t) \cdot G_2(t)}\cos(\Delta\phi)\right], \qquad (7)$$

$$P_{out,2}(t) = 0.125 P_{in}(t) \cdot \left[G_1(t) + G_2(t) + 2\sqrt{G_1(t) \cdot G_2(t)}\cos(\Delta\phi)\right], \qquad (8)$$

where $\Delta\phi = -0.5\alpha_{LEF} \ln(G_1 / G_2)$, α_{LEF} is the line width enhancement factor, G_1 and G_2 are the temporal gain profiles of the SOA 1 and 2, respectively [16].

To obtain an expression for the SW, the output signal power $P_{out,1}(t)$ in (7) is normalised with respect to the input power $P_{in}(t)$, as given in:

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$$W_i(t) = 0.125\left[G_1(t) + G_2(t) - 2\sqrt{G_1(t)G_2(t)}\cos(\Delta\phi)\right] \qquad (9)$$

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~~$W_i(t) = 0.125\left[G_1(t) + G_2(t) - 2\sqrt{G_1(t)G_2(t)}\cos(\Delta\phi)\right]$. (9)~~

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According to (9), the SMZ switch can provide an additional gain to the target signal, thus ensuring that the SW gain > 1. To solve (9) one needs to know precise value of α_{LEF} and the gain profiles of the data signals at the output of the SOA1 and SOA2, respectively.

2.2 Bit error rate (BER) analysis

The system model for the BER analysis is adapted from [14] and~~,~~ [15]. Based on Fig. 1, we can derive an expression for the BER ~~taking~~ which takes into account all the noise sources and channel ~~crosstalk (~~*CXT*~~)~~. The main sources of the noise are the relative intensity noise (*RIN*), SOA spontaneous emission (ASE), and noises associated with the receiver. It is assumed that noise associated with the source is negligible. *RIN* is caused by the combination of the timing jitters (mainly introduced by the ASE noise of lumped optical amplifier) between the control and signal pulses and a non-square SW profile of the SMZ, thus resulting in the intensity fluctuation of target signals and in the switching power penalty. *RIN* is defined in terms of the variance $V(\tau)$ and the expected value $E[w(\tau)]$ of the target signal energy which is given as [14]:

$$RIN(\tau) = \frac{V(\tau)}{E^2[w(\tau)]} \qquad (10)$$

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A non-ideal SW with a finite extinction ratio (ER) will result in *CXT*. *CXT* is defined in terms of non-target channels and target channel powers $P_{o\text{-}nt}$ and P_{ot}, respectively which is given by:

$$CXT = 10\log_{10}\left[\frac{P_{o-nt}}{P_{o-t}} = \frac{\frac{1}{T_c}\int_{t_0+T_b/2}^{t_0+T_c-T_b/2} W(t)\,p_p(t-t_0)\,dt}{\frac{1}{T_c}\int_{t_0-T_b/2}^{t_0+T_b/2} W(t)\,p_p(t-t_0)\,dt}\right], \qquad (11)$$

where $p_p(t)$ is the periodic train of data signal, T_b is the data bit duration, t_0 is the centre of the SW, and T_c is the CP period. One interesting characteristic of SMZ switch is that both data and control signals co-propagate within the switch, thus resulting in reduced residual *CXT*~~crosstalk~~ compared with the TOAD-based switches where a small ~~cross-phase modulation~~XPM between the counter-propagating

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pulses results in residual *CXT*~~crosstalk~~ [12],[20]. With reference to Fig. 3, the normalis~~z~~ed total output power of two cascading SMZ stages induced *CXT* is computed by:

$$P_o = P_i(1+CXT_1)(1+CXT_2) = P_i(1+CXT_t) \qquad (12)$$

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$$P_o = P_i(1+CXT_1)(1+CXT_2) = P_i(1+CXT_t)$$

~~(12)~~

~~Where~~ where the total *CXT*~~crosstalk~~ defined in terms of the 1st and 2nd stages ~~is~~ $(CXT_t = CXT_1 + CXT_2 + CXT_1 CXT_2)$, and P_i, P_o are the powers at the input and output of ~~two~~ two-stage SMZ, respectively.

The mean photocurrents for mark I_m, and space I_s are given as [14],[15],[21]:

$$\begin{aligned} \bar{I}_m &= K \times (2P_s) \times (1+CXT_t) \\ \bar{I}_s &= K \times (2P_s) \times (CXT_t) \end{aligned} \qquad (13)$$

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$$\begin{aligned} \bar{I}_m &= K \times (2P_s) \times (1+CXT_t) \\ \bar{I}_s &= K \times (2P_s) \times (CXT_t) \end{aligned}$$

~~(13)~~

where $K = \eta_{amp2\text{-}in} G_{amp2} \eta_{amp2\text{-}out} L_{of} R_p$, R_p is the responsivity of the photodetector, $\eta_{amp2\text{-}in}$ and $\eta_{amp2\text{-}out}$ are the input and output coupling efficiencies of pre-amplifier, respectively, G_{amp2} is the pre-amplifier gain, L_{of} is the optical filter loss, and P_s is the average received power without CXT. Assuming that the probabilities of the transmitted mark and space are equally likely (i.e. 0.5), the average received power for mark ~~(only)~~ is $2P_s$.

With reference to Fig. 3, the system is composed of four cascading amplification stages, thus the total noise figure NF_{tot} ~~defined in terms of the noise figures~~ for all stages is given as[22]:

$$NF_{tot} = NF_{amp1} + \frac{NF_{SW}}{G_{amp1}} + \frac{NF_{demux}}{G_{amp1}G_{SW}} + \frac{NF_{amp2}}{G_{amp1}G_{SW}G_{demux}} \qquad (14)$$

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The average photo-current equivalent of ASE ~~and~~ is given by [14],[15],[22]:

$$I_{ASE-tot} = 0.5\, NF_{tot}\, G_{tot}\, \eta_{amp\,2-out}\, q B_o L_{of} \qquad (15)$$

where $G_{tot} = G_{amp1} \times G_{SW} \times G_{demux} \times G_{amp2}$, B_o is the optical bandwidths and q is the electron charge.

The noise sources contributing to the deterioration of the signal are the *RIN* σ^2_{RIN} from the source and from the last SMZ (i.e. SMZ-demux because of its narrow SW compared to the SMZ of the switch within the router), the ASE of SOAs in SMZ and pre-amplifier σ^2_{amp} and the shot noise σ^2_s and thermal noise σ^2_{th} at the receiver $\sigma^2_{receiver,x}$, defined as [14],[15]:

$$\sigma^2_{RIN,m} = \overline{I_m^2} RIN_T B_e + (2P_s K)^2 RIN_{SMZ-demux} \quad (16)$$

$$\sigma^2_{RIN,s} = \overline{I_s^2} RIN_T B_e \quad (17)$$

$$\sigma^2_{amp,x} = \frac{4\overline{I_x} I_{ASE-tot} B_e}{B_o} + \frac{I^2_{ASE-tot}\left(2B_o - B_e\right)B_e}{B_o^2} \quad (18)$$

$$\sigma^2_{receiver,x} = 2q\left(\overline{I_x} + I_{ASE-tot}\right)B_e + \left(\frac{4kT_k}{R_L} + i_a^2\right)B_e \quad (19)$$

where RIN_T is the RIN of the transmitter. Here we only consider RIN contribution from the last SMZ stage~~-~~, RIN_{SMZ} can be computed from [14] for a given value of RMS_{jitter}. B_e is the electrical bandwidth of the receiver, x represents mark or space, k is the Boltzman's constant, T_k is the temperature in Kelvin, R_L is the load resistance of photodetector and i_a^2 is the power spectral density of the electrical amplifier input noise current.

In (18), 1st and 2nd terms are the variances of the signal-ASE beat noise σ^2_{S-ASE} and the ASE-ASE beat noise $\sigma^2_{ASE-ASE}$, respectively, whereas in (19) 1st, 3rd and 4th terms represent σ^2_s, σ^2_{th}, and the amplifier noise, respectively. All noise sources are considered to be uncorrelated. As $B_o >> B_e$, the beat noise is considered with Gaussian approximation. The total variance of noises is given by:

$$\sigma^2_{t,x} = \sigma^2_{RIN,x} + \sigma^2_{amp,x} + \sigma^2_{receiver,x} \quad (20)$$

Adopting the same approach used in [14],[15],[21] the BER is given by:

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \quad (21)$$

where

$$Q = \frac{\overline{I_m} - \overline{I_s}}{\sigma_{t,m} + \sigma_{t,s}} \quad (22)$$

$$\cancel{Q = \frac{\overline{I_m} - \overline{I_s}}{\sigma_{t,m} + \sigma_{t,s}}} \quad \cancel{(22)}$$

We performed the analysis in order to investigate the BER against the receiver sensitivity.

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3.0 Simulation Model and Results

The proposed system shown in Fig. 1 is simulated using the Virtual Photonic® (VPI) package, as shown in Fig. 4. The OTDM transmitter is composed of a single continuous-~~-~~wave laser source at the wavelength of 1550 nm, a number of M-Z external modulators (modulated at the base rate of 2.5 Gbps), and a number of fibre delay lines. The laser sources used at the OTDM node to generate OTDM packets have a 3 ps pulse width at the same wavelength of 1550 nm. The CP peak power depends ~~Depending~~ on the size of the required SW at a particular SMZ~~, the CP will have different peak power~~. For the 1×M switch and demultiplexer modules the ~~CPS~~ CPs have peak power of 215 and 90 mW, respectively. The CPs are passed through a 90^o orthogonal polarizer to distinguish it from the 1 mW data pulse ~~with a peak power of 1mW~~ since both are at the same wavelength. OFDLs are used to provide the delay T_{delay} between the two CPs at the input of the SMZ ~~are for~~and time synchronis~~z~~ation between the control and data pulses. Simulation results for the BER performance is compared with the predicted data. Here we first investigate the characteristic of the SMZ, 1 *x M* OTDM router and demultiplexer followed by the system BER.

(i) *SMZ switch*: Two methods have been used to evaluate the SW of the SMZ: a numerical model (modified version of [23]), and a VPI® ~~based~~ model (see Fig. 4). All the parameters used in the simulation are listed in Table I. The full wave at half maximum (FWHM) of pulses used is 3 ps which less than the transition time of the SOA with a length of 0.25 μm. For T_{delay} = 10 ps the predicted gain profiles of data pulses, having propagated through the SOAs, are shown in Fig. 5. In the absence of CP, a data pulse that passes through the SOAs ~~and~~ experienced an initial gain of 20.1 dB. The gain profile drop rapidly to a value of 2.8 dB after a high power and short duration CP saturates the SOAs. With identical gain profile, the SMZ SW profiles for a range of SW width (1-10 ps) are shown in the inset of Fig. 5. ~~Also shown are SW profiles with different widths.~~

Using (10) and (11) the SMZ *RIN* for different values of the RMS_{jitter} are shown in Fig. 6(a). When the RMS_{jitter} increases, the RIN deteriorates particularly for narrower SW width. The maximum *RIN* values are approximately -24, -18 and -10 dB for RMS_{jitter} values of 0.5, 1 and 2 ps, respectively. The *RIN* decreases as the SW width increases reaching a minimum value of ≈ -25 dB for almost all values of RMS_{jitter}. Demultiplexing of non-target channels from the adjacent channels will occur unless the SW width is comparable to or smaller than the time slot of OTDM channels (but > FWHM of the pulse).

Figure 6(b) shows *CXT* against the SW width (or T_{delay}) for the SOA length of 0.25 mm ~~and~~ at different OTDM ~~total bit~~ data rates. For all data rates *CXT* increases with the SW size. The B-B system at 2.5 Gbps ~~system~~ gives the best *CXT* performance, whereas at high data rates ~~(i.e.~~of 100 and 200 Gbps~~)~~ ~~display much higher~~ the *CXT* is much higher, with a maximum values of 0 and -4 dB respectively ~~reached at~~for the SW width of 20 ps (a very wide SW).

(ii) 1 *x M* OTDM router and demultiplexer:~~-~~ The OTDM packet after propagating through a long length of fibre and SOAs, see Fig. 7(a), is split~~ed~~ and fed into the clock and address extraction, and the main switch (with dedicated delay) modules. The extracted CS with a high ER of 30 dB is shown in Fig. 7(b). Figure 7(c) shows the extracted address bit stream used as the CP in 1 X *M* switch for forwarding the whole OTDM packet to the correct output port as shown in Fig. 7(d). From Fig. 7(d) the ER is about 50 dB compared with 24 dB for the input OTDM packet, this 36 dB gain in ER is due to low residual gain outside the SMZ SW (see Fig. 5). The recovered OTDM channel at output of the demultiplexer is shown in Fig. 7(e) with ER of 44 dB. The drop in ER is due to the noise associated with the SOA within the demultiplexer.

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3.1 BER Results

We have used theoretical and simulation methods to evaluate the BER performance of the OTDM node with a router and a demultiplexer. In the simulation we evaluated the BER for RZ pseudo random binary sequence (PRBS) of length of 2^{13} -1 and equal probability for mark and space. The B-B ~~(base line)~~ bit rate is ~~at~~ 2.5 Gbps with return-to-zero (RZ) pulse format to ensure that intersymbol interference induced by post-detection electrical filtering has ~~very little~~minimal impact. All the receiver sensitivity measures are referred to an average BER of 10^{-9}. All important system parameters are adopted from experimental work reported in [10],[17] and ~~,~~[24] are listed in Table 1. In VPI®, BER estimation is based on sampled signals with noise represented in noise bins by using the global parameters. The noise bins carry the statistical information of the noise ~~statistics~~. Figure 8(a) shows the measured and simulated BER curves for the 2.5 Gbps B-B, ~~and~~ 100 and 200 ~~Gb/s~~Gbps OTDM packets. The average received optical power P_{rx} was measured for 2.5 Gbps B-B at the input of the optical receiver. For all measurements it was ensured that the overall system gain is kept at 25 dB with the same optical receiver parameters. For high SOA gains the signal-ASE and the ASE-ASE beat noises becomes dominant, and the optical receiver sensitivity depends on the B_o.

As shown in Fig. 8(a), for the 2.5 Gbps B-B without a router-demultiplexer the calculated and simulated curves show good agreement, with only a small difference of < 0.4 dB at BER of 10^{-9}. For 100 and 200 Gbps incorporating a router and a demultiplexer, the predicted BER curves show comparable characteristics, whereas the simulated curves are slightly ~~worth~~ worse with power penalties of 0.5 and 1 dB at BER of 10^{-9} for 100 and 200 Gbps, respectively. Compared with the B-B case, at BER of 10^{-9} the combined power penalties for the router and demultiplexer are about 2 and 2.5 dB for 100 and 200 ~~Gb/s~~Gbps, respectively. For BER < 10^{-9} the simulated power penalties increase by a few dB compared with predicted results. The most probable causes of the power penalties are mainly due to the *RIN* and ~~related~~ ASE associated with SMZs and various insertion losses. Note that the SMZ switch with ER (> 30 dB) ~~resulted~~ results in time-switching with ERs in excess of 50 dB, effectively eliminating *CXT* interference. An intersection of BER curves at BER of 10^{-4} and 10^{-5} is explained as follow. In VPI® ~~based~~ model the BER estimation is based on the bit stream reference, thus providing more accurate results for low values of *Q* (i.e. BER > 10^{-4}) in contrast to the predicted results. Finally, Fig. 8(b) shows the simulated eye diagrams at the output $y_o(t)$ of optical receiver for a single channel OTDM at BER of 10^{-9}.

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4. Conclusions

We have proposed and simulated an OTDM node with an all-optical packet router employing a 1×M SMZ switch, and a demultiplexer for 100 and 200 ~~Gb/s~~Gbps bit rates. Simulation results demonstrated that clock recovery, address recognition, packet routing and OTDM channel demultiplexing is possible with very little or no crosstalk at all. We investigated the BER performances numerically and by means of software simulation which ~~showing~~ showed good agreement. For BER of 10^{-9}, the power penalty incurred are about 2 and 2.5 dB for 100 and 200 ~~Gb/s~~Gbps, respectively compared with 2.5 Gbps ~~back-to-back~~B-B case. The main contributors to power penalties are the *RIN* and ASE of the SMZs and SOAs, respectively. The router proposed has a great potential for future ultra-high speed all-optical OTDM packet switched networks.

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List of Table and Figures