INVESTIGATION OF ALL-OPTICAL SWITCHING OCDMA TESTBED UNDER THE INFLUENCE OF CHROMATIC DISPERSION AND TIMING JITTER

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ABSTRACT

First part of this paper presents an all-optical switching OCDMA testbed investigation under the influence of the residual chromatic dispersion resulted from different locations of the receiving terminal. The investigation was carried out using incoherent 2D-WH/TS OCDMA codes based on picosecond pulses at OC-48 (2.5Gb/s) data rate. The testbed itself is based on a fully chromatic dispersion compensated (with sub-picosecond accuracy) 17 km bidirectional fiber link connecting University of Strathclyde and Glasgow University. We have found that a high performance penalty in the form of BER deterioration was incurred when even a relatively short length of optical fiber was added to a fully compensated transmission link in order to relocate the receiving terminal (we tested increments up to 275m of SMF-28). Second part of this paper reports on the testbed performance when an OCDMA receiver with built in all-optical clock recovery was implemented to mitigate the detrimental effects of the link timing jitter on the picosecond switching based all-optical time gate.

KEYWORDS: *Optical code division multiple access, Chromatic dispersion compensation, 2D-WH/TS codes, All-optical clock recovery, Picosecond all-optical switching*

1.0 INTRODUCTION

Optical Code Division Multiple Access (OCDMA) technology offers capabilities which enable multiple users to share bandwidth simultaneously and access network resources asynchronously. The potential to enhance privacy and information security, improve spectral efficiency, flexibility and high scalability (Bres, Glesk & Prucnal, 2005), (Bres et al., 2007) makes the OCDMA an attractive and promising technique for next generation networking applications (Nishimura, 2005). Different approaches of coherent and incoherent OCDMA

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have been extensively investigated (Agrawal, 2001), (Bres et al., 2007), (Wang & Kitayama, 2004), (Osadola et al, 2011) with lots of attention geared towards developing various coding schemes (Yang & Kwong, 2002). The use of 2-dimensional wavelength-hopping/time-spreading (2D-WH/TS) family of codes has been widely researched for possible use in different future OCDMA applications (Huang et al., 2007). These codes are characterized by the combination of time spreading and wavelength hopping of picosecond pulse patterns which spreads optical pulses in both the time and wavelength domain simultaneously thus achieving code flexibility as well as better performance (Jyoti & Kaler, 2010), (Osadola, et al., 2012). Among the advantages are including reduced cross correlation, increased cardinality and nonexistence of autocorrelation side lobes (Dang, Pham & Cheng, 2009), (Minato et al., 2005). Widely studied has been the family of prime codes (Dang, Pham & Cheng, 2009), (Prucnal, 2005) employing multiwavelength short pulses for codes generation.

However, the result of broad spectrum of short optical pulses and when considering the different propagation speed of each spectral component, the multi wavelength pulses within the OCDMA code start to broaden as the result of propagation in a dispersive medium (Chua, 2002), (Yang et al., 2008). In 2D-WH/TS codes that utilize short picosecond pulses for code generation, the effect of chromatic dispersion will be very severe especially because the relative broadening due to fiber chromatic dispersion (Prucnal, 2005), (Ng, Weichenberg & Sargent, 2002), (Osadola et al., 2013) can become of the order of the pulsewidth even after relatively short propagation distance in a single mode optical fiber. It is in view of these that makes controlling chromatic dispersion one of the key factors for preventing significant degradation in OCDMA. To our knowledge not much of study has been done in terms of learning the extent to which small or even residual amount of chromatic dispersion in transmission link can affect performance of OCDMA systems that utilize multiwavelength picosecond pulses for 2D-WH/TS code creation. In communications systems, there is always a need to extend the reach of the existing fiber link or to relocate the user terminals. In the event of this, a simple addition of extra length of fiber would mean also adding some amount of dispersion. Therefore, it is necessary to understand how chromatic dispersion accumulated via fiber link extensions (say up to few hundreds of meters of SMF-28) may affect the overall OCDMA system performance.

Beside the chromatic dispersion impairments, the performance is also influenced by the timing jitter. This is even more true for the coding sheme using 2D-WH/TS OCDMA codes with multicolor ps pulses

(Osadola et al., 2013). The effect of the timing can be mitigated by using a self-synchronize OCDMA receiver with built-in all-optical clock recovery (Idris, Osadola & Glesk, 2012).

In this paper we report results of our performance investigation of the 17 km long bidirectional OCDMA fiber optic testbed connecting University of Strathclyde and Glasgow University under the influence of relatively small deviations from its fully chromatic dispersion compensation due to its terminal relocations. The investigations are carried out using incoherent 2D-WH/TS OCDMA codes based on picosecond pulses at OC-48 (2.5Gb/s) bit rate. Second part of this paper reports on performance improvements in the system when the OCDMA receiver is equip with a build-in all-optical clock recovery in order to mitigate the detrimental effects of the timing jitter on a time gate during a picosecond all-optical switching operation.

2.0 BACKGROUND

2.1 Chromatic dispersion

Chromatic dispersion occurs as result of the fact that the different spectral components of the optical pulse travel in fiber at slightly different group velocities. The frequency dependence of the group velocity leads to a pulse broadening because different spectral components of the pulse will disperse during propagation in optical fiber and do not arrive simultaneously. For pulse propagation distance L in a SMF, if $\Delta\omega$ is pulse spectral width and v_g is the group velocity, the extent of pulse broadening can be written (Agrawal, 2002)

$$\Delta\tau = \frac{d\tau}{d\omega}\Delta\omega = \frac{d}{d\omega}\left(\frac{L}{v_g}\right)\Delta\omega = L\frac{d^2\beta}{d\omega^2}\Delta\omega = L\beta_2\Delta\omega. \quad (1)$$

where β_2(ps²/(km)) is called group velocity dispersion parameter (GVD) (Agrawal, 2001). By substituting $\omega = 2\pi c/\lambda$ and using $\Delta\omega = (-2\pi c/\lambda^2)\Delta\lambda$ we get

$$\Delta\tau = \frac{d}{d\lambda}\left(\frac{L}{v_g}\right)\Delta\lambda = DL\Delta\lambda \quad (2)$$

where $D = -\frac{2\pi c}{\lambda^2}\beta_2.$

D is called a dispersion parameter and is expressed in ps/km-nm and varies with the wavelength.

2.2 All-optical clock recovery for timing jitter supression and optical switching control

Transmitted optical signals at high data rates over longer distances often suffer from timing jitter. This leads to problems with a receiver synchronization resulting in BER degradation. Accurate and "dynamic" synchronization of the receiver is therefore needed to improve signal detection to ensure that the OCDMA receiver is as little as possible affected by the timing jitter. A clock recovery for the receiver synchronization is a well-known approach for suppressing detrimental effects of timing jitter on the quality of received data. Clock recovery subsystems have been recognized as very essential for high speed detection systems (Prucnal, 2005), (Lerber et al., 2009). Implementations of wide variety of clock extraction techniques for use in receiver synchronization were predominantly developed for wavelength division multiplexing (WDM) (Vlachos, 2000), (Su et al., 2000) and optical time division multiplexing (OTDM) (Lui et al., 2008), (Zhang et al., 2010) systems. However, their application in OCDMA which uses picosecond pulses is limited or often impossible. Clock and data recovery techniques for such OCDMA systems were reported by (Deng et al., 2009), (Faucher et al., 2005). However, these approaches were not implemented all-optically and can not be used for all-optical data post-processing. Optical clock extraction was demonstrated by using a nonlinear optical loop mirror (NOLM) and terahertz optical asymmetric multiplexer (TOAD) (Kravtsov, 2009), (Sokoloff et al., 1993), respectively. However, a practical realization of a suitable all-optical clock recovery circuit which will generate optical clock signal from the incoming OCDMA data stream without any intermediate electronic stage is not a simple task. Recovering an optical clock from incoming data at a given bit rate means extracting a periodic signal with period reciprocal of the bit rate, while keeping it free of information carried by data and without the phase noise. Such optical signal can be then used to control an all-optical picosecond switch or time gate for its precise timing control to open and close its switching windows. A variety of high speed all-optical switching devices based on semiconductor optical amplifiers (SOA) (Nakamura, Ueno & Tajima, 2002), (Bakopoulos et al., 2005), (Minh, Gbassemlooy & Ng, 2006) or based on nano-wire/ sub-wavelength Mach-Zehnder interferometric (MZI) waveguide structures (Glesk et al., 2011) were reported and successfully demonstrated. The operation of interferometric switches is straightforward and requires optical picosecond clock pulses to control their operation. Conceptually, the switching is achieved by optically inducing a relative differential phase shifts between both MZ arms. The carrier dynamics enables these switches to operate at ultra-high data rates well beyond the speed of the current electronics. In order to avoid possible timing jitter impairments on the switching performance of these all-optical gates the optical clock should be preferably recovered from the incoming data stream.

3.0 EXPERIMENTAL RESULT

Before our investigations, the 17 km bidirectional fiber optic testbed between University of Strathclyde and Glasgow University was compensated for chromatic dispersion (see Figure 1). We used a fiber based chromatic dispersion compensation (CDC) technique.

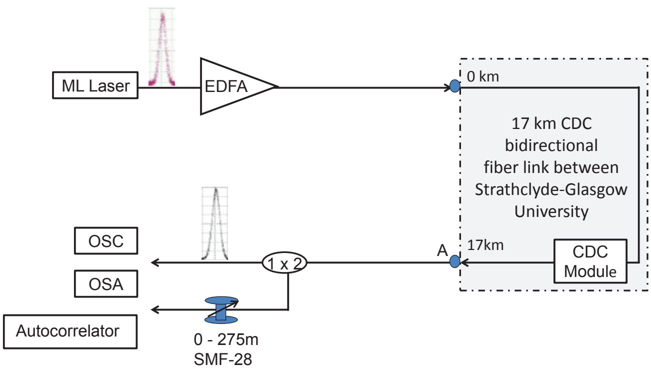


Figure 1. Experimental setup to evaluate impact of chromatic dispersion on a single laser pulse

First a commercially available CDC module was applied. Then fine tuning of the entire fiber link was performed to achieve sub-picosecond compensation accuracy for the spectral region which is used by the 2D-WH/TS OCDMA codes based on multiwavelength picosecond pulses. Figure 1 illustrates the experimental setup we used to verify the accuracy of our CDC and also to measure the residual chromatic dispersion (CD) of the entire link due to its length changes resulted from moving the receiving terminal to its future locations. First from OTDR measurements we estimated the link length between the transmitting modelocked laser (MLL) and point A to be 17 km (Figure 1). Then we compared the output pulse width from the MLL before and after its propagation inside the 17 km long CD compensated fiber link. The laser pulse was monitored using an (Agilent 86105B digital communications analyzer) with 60GHz oscilloscope, optical spectrum analyzer (Agilent 86146B) and an optical autocorrelator. Figure 2(a) and (b) shows the temporal traces of the outgoing and the received laser pulse, respectively measured by optical autocorrelator (Femtochrome).

The outgoing laser pulse width was 2 ps full wave at half maximum (FWHM), and the received pulse after propagation in the 17 km long CD compensated transmission link in Figure 1 was 2.2 ps. By comparing both results it was found 0.2 ps broadening which is 10% of FWHM value for the outgoing pulse.

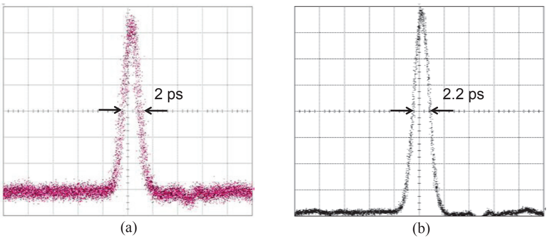


Figure 2. FWHM of laser pulse; (a) before and (b) after propagation in the 17 km link treated for chromatic dispersion

To demonstrate how severely deviation from the link with full CDC can affect this 2 ps optical pulse due to terminal relocation we conducted additional experiments. Obtained results are summarized in Figure 3. Here for example we can see that extending the 17 km long fully CD compensated link (in order to move the terminal by 275 m) by adding 275 m of SMF-28 will lead to 250% pulse broadening. Obtained experimental results are in good agreement with the simulated values (see dotted line in Figure 3). It should be noted that before different sections of SMF-28 fiber were added the laser pulsewidth in this experiment was 2.2 ps FWHM as can be seen in Figure 2.

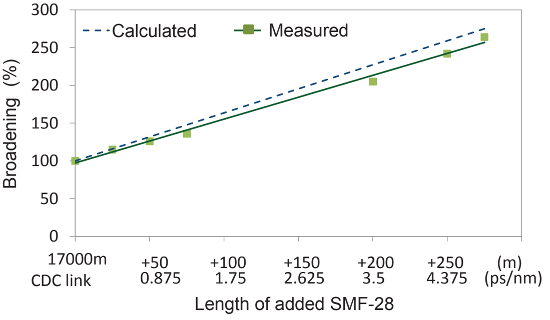


Figure 3. Illustration of relative laser pulse broadening as a result of accumulated chromatic dispersion

Similarly, we verified the effect of the fiber link on the propagation of a single 2D-WH/TS OCDMA code which is based on multiwavelength picosecond pulses. The experimental setup is shown in Figure 4. We used 2D-(4,50) WH/TS family of OCDMA codes represented by four wavelength pulses λ_1 = 1551.72 nm, λ_2 =1550.92 nm, λ_3 = 1552.52 nm, λ_4= 1550.12 nm which were placed accordingly within 50 time chips with duration of 8 ps. The sequence is as follows: 1-λ_3, 9-λ_2, 28-λ_4, and 31-λ_1 (see Figure 5). The numbering indicates the chip's order. The code length was 400 ps and corresponds to the data transmission rate of OC-48 (2.5G bp/s).

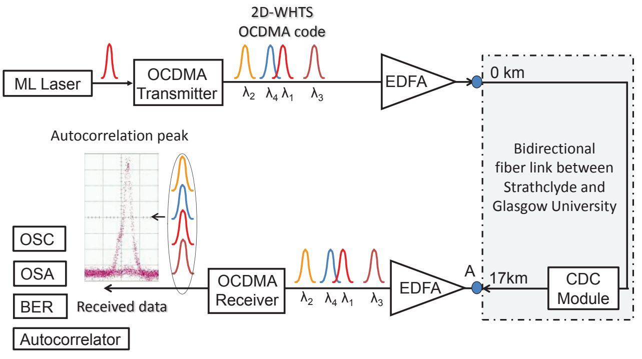


Figure 4. Experimental setup to evaluate impact of chromatic dispersion on 2D WH/TS OCDMA code

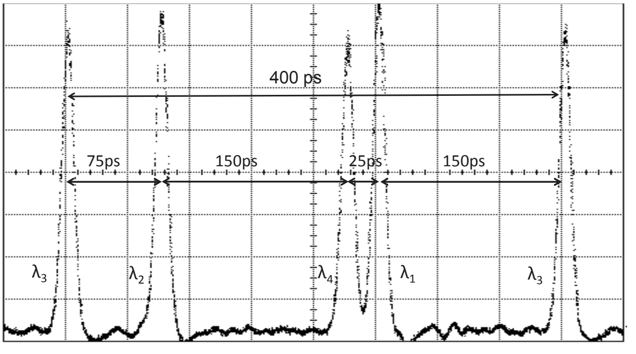
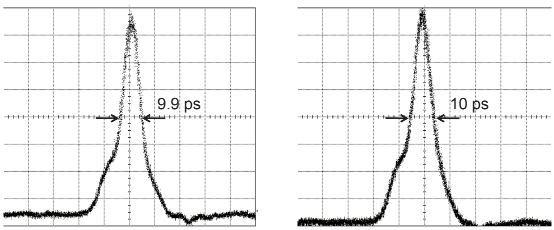


Figure 5. 2D (4, 50) Wavelength-Hopping/Time-Spreading code (1-λ3, 9-λ2, 28-λ4, and 31-λ1), as seen on a bandwidth limited oscilloscope

Our measurement results are shown in Figure 6(a) and (b) and depict autocorrelation peak for the back to back measurement and after 17 km of code propagation in CDC fiber link (see Figure 4), respectively. It is worthy of note that dispersion slope compensation over the range of wavelengths in the OCDMA code was taken into account when choosing the CDC module. The respective autocorrelations were obtained by decoding the received signal by the matched OCDMA receiver as is schematically shown in Figure 4. The observed uneven (asymmetric) autocorrelation shape in Figure 6(a) and (b) can be explained by manufacturing imperfections of the matched OCDMA encoder and decoder pare. By comparing both autocorrelation peaks side by side we can see 0.1 ps mismatch in their temporal width caused by the residual fiber link chromatic dispersion which is within ~10% of the back to back value of the autocorrelation peak width measurement. This 10% CDC accuracy achieved for the autocorrelation peak containing 4 wavelengths (note the code weight 4 for used OCDMA codes) is the same as the accuracy achieved for the single wavelength laser pulse seen in Figure 2. This can be interpreted that the dispersion slope compensation over the range of used wavelengths used by the OCDMA was also achieved.



(a) (b)

Figure 6. Autocorrelation peaks obtained from (a) back to back measurements and (b) after OCDMA code propagation in 17 km CD compensated transmission link between Strathclyde and Glasgow University

3.1 Impact of varying chromatic dispersion on OCDMA system performance in a multiuser environment

The study was carried out using the setup shown in Figure 7. The bit error rate was measured for different receiving terminal locations from the point A where the link is fully CD compensated (+50 m, +200 m, +250 m and +275 m from the point A). An adequate power control was implemented to eliminate the influence of loss associated with the increased fiber link lengths.

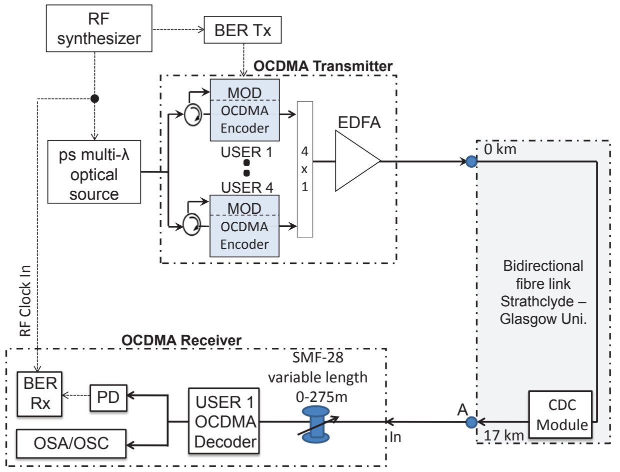


Figure 7. Multi user OCDMA testbed with the implemented chromatic dispersion compensation

In order to generate four user data traffic based on 2D-WH/TS Optical CDMA codes, first a spectral slicing of optical supercontinuum was performed by Fiber Bragg Gratings (OKI FBG) based OCDMA encoders. Mach-Zehnder data modulator driven at OC-48 by a 2^{31}-1 PRBS from an Agilent N4903A series bit error rate tester was used to generate data. Traffic from all users was then combined and launched via EDFA into the CD compensated Strathclyde – Glasgow University fiber link. The received OCDMA signal was then decoded using an FBG decoder matched to the User 1 encoder. The decoded signal was then sent through attenuators (Agilent 8157A) to a bit error rate tester having an 11GHz optical receiver with -18 dB sensitivity (Nortel PP10G) as its front end and as needed the decoded OCDMA signal was monitored using an oscilloscope, optical autocorrelator, and optical spectrum analyzer. Figure 8 shows obtained bit error rate curves when four simultaneous users were broadcasting on the network. No error floor was observed.

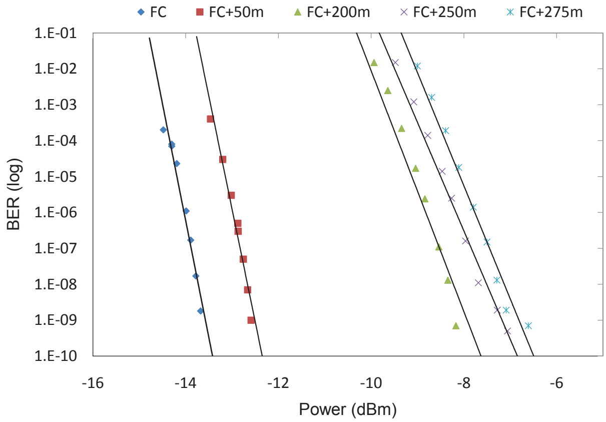


Figure 8. BER system performance measurements for different level of "residual" chromatic dispersion on the network created by adding SMF-28 to 17 km long fully CD compensated fiber link. FC - indicate BER of the system for fully CD compensated 17 km long fiber link between Strathclyde and Glasgow University

The effect of the added CD on the overall user 1 data reception due to moving this receiving terminal to different locations from the point A (where the link is fully compensated) can be seen in Figure 8. Obtained results suggest that to achieve a targeted BER performance of 10-9, moving the terminal by 275 m will result in a 7 dB power penalty if no chromatic dispersion is accompanying this terminal relocation. On the other hand moving the terminal just 50 m will lead to only 1 dB of power penalty. It is important to note again that these penalties are unrelated to power losses due to added extra length of SMF-28 since we compensated for these additional losses prior taking BER measurements.

The observed performance degradation could be explained by the fact that the introduced CD causes broadening of multi wavelength pulses within the OCDMA codes and also their time skewing. This will impact the autocorrelation peak in our case composed of four wavelengths which when unaffected has the theoretical weight of four (i.e., height of 4 pulses). However in the presence of the dispersion this is not true anymore. It can be seen from Figure 9 that the time skewing misaligns the perfect time overlap of pulses creating the correlation peak thus lowers and broadens the shape of the autocorrelation peak. In the multi user environment cross correlations will also experience chromatic dispersion broadening. From Figure 3 done for single wavelength measurements we can estimate that by moving the terminal by 275 m will result in 275% broadening of pulses which represent the 2D-

WH/TS OCDMA code thus considerably increasing the multi-access interference and the crosstalk in the multiuser environment.

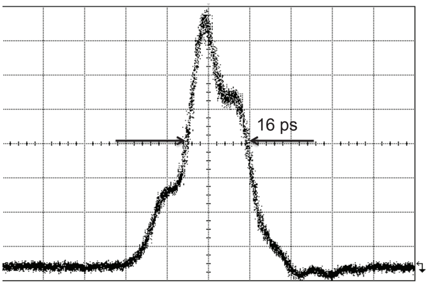


Figure 9. Autocorrelation peak as seen on the oscilloscope after 17 km OCDMA transmission in CD compensated fiber link followed by an extra 200 m SMF-28

Obtained results suggest that even if relatively short distance terminal relocations are required they shoud be done by using fully CD compensated fiber spans to maintain OCDMA system performance.

3.2 Demonstration of OCDMA receiver with built-in all-optical clock recovery for ultrafast all-optical switching control

The OCDMA testbed in Figure 7 was now retro fitted with an OCDMA receiver with built-in all-optical clock recovery (AOCR), (Idris, Tolulope & Glesk, 2012) as is shown in Figure 10.

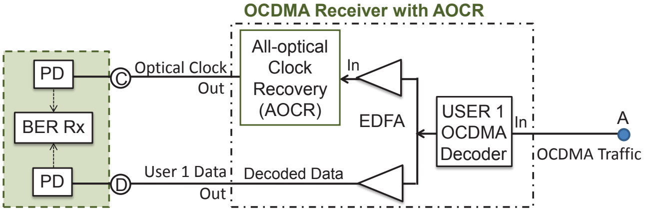


Figure 10. Receiver side with built-in all-optical clock recovery (AOCR) under the test in the testbed

Its performance was evaluated by taking the BER measurements and by recording eye diagram using an Agilent N4903A bit error tester. Our obtained results are in Figure 11. No error floor was observed.

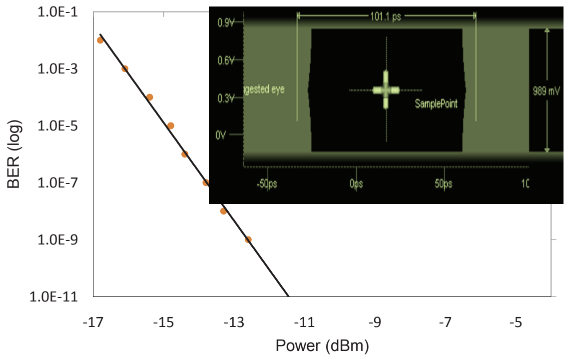


Figure 11. BER and the eye diagram for the user 1 received by using an OCDMA receiver with a built-in all-optical clock recovery as recorded by BER tester

In our next experiment the AOCR was then used to drive a 2x2 all optical time gate to filter out autocorrelation signal representing the received OCDMA data (see Figure 12). Here an optical delay line (ODL) was used to set the proper timing between the incoming OCDMA data (autocorrelation peak) and the recovered optical clock. The output of the time gate was monitored by using 20GHz bandwidth limited digitizing oscilloscope with optical sampling head (Agilent 86105B). A clear eye signal was recorded as shown in Figure 12 indicating effective timing jitter supression.

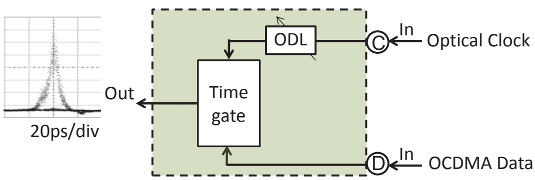


Figure 12. All-optical switching demonstration with all-optical switch/ time gate controlled by all-optically recovered clock from the received OCDMA signal

4.0 CONCLUSION

We have presented results of our field based investigation of the OCDMA system under the varying influence the chromatic dispersion using a 17 km long testbed between Strathclyde and Glasgow University. The investigations were carried out using incoherent OCDMA system with four simultaneous users each using 2D-WH/TS OCDMA codes based on multiwavelength picosecond pulses. We found that high penalty was incurred by adding relatively short length of single mode SMF-

28 fiber to a fully chromatically dispersion compensated 17 km long transmission link. Then the testbed was fitted with OCDMA receiver with a built-in all optical clock recovery to addressed synchronization all-optical time gate under the influence of timing jitter. The all-optically recoverd clock was then used to control all-optical gate resulting in error free operation and a clean eye diagram.

5.0 ACKNOWLEDGEMENT

Siti Idris is on leave from Universiti Teknikal Malaysia Melaka (UTeM) and her PhD work is supported by the Ministry of Higher Education Malaysia.

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