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Managing Dispersion Affected OCDMA Auto-correlation Based on PS Multi-wavelength Code Carriers Using SOA

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***Abstract*—Distortion of the OCDMA auto-correlation width by fiber chromatic dispersion can severely influence incoherent OCDMA transmission based on picosecond multi-wavelength pulses. To the best of our knowledge, we report for the first time the use of SOA for manipulation of the OCDMA auto-correlation consisted of multi-wavelength code carriers in order to provide needed compensation. The OCDMA transmission system was based on two-dimensional wavelength-hopping time-spreading (2D-WH/TS) codes with 8 ps multi-wavelength pulses as the code carriers. Different techniques deploying SOA for auto-correlation width adjustment were investigated and their effectiveness was subsequently verified on the OCDMA transmission through a 17 km long fiber optic testbed connecting Strathclyde and Glasgow Universities.**

***Index Terms*—Incoherent OCDMA, chromatic dispersion, chirp, gain dynamics, semiconductor optical amplifier.**

I. Introduction

Chromatic dispersion management is important for high data rate incoherent fiber-optic communication [1] but is essential for incoherent OCDMA transmission based on schemes using multi-wavelength picosecond code carriers [2,3]. As these code carrier pulses are short, transmitted codes will be strongly affected by CD even if the transmission distance will change by a few meters. One example is the addition of an optical fiber in order to relocate the OCDMA transmitter or receiver [2]. If CD is not properly implemented, the recovered OCDMA auto-correlation by an OCDMA decoder will show temporal skewing amongst individual wavelength code carriers thereby severely impacting OCDMA system performance [3]. The impact of CD on 2D-WH/TS codes was analyzed in [4]. It has been shown that the CD related pulse distortion and related time skewing will cause undesirable broadening of recovered OCDMA auto-correlation. The auto-correlation surrounding cross-correlation will be also impacted by CD leading to reduced auto-to-cross-correlation ratio. This in turn will increase the multi-access interference noise and crosstalk leading to performance degradation and a drastic reduction in the number of simultaneous users [4]. To fully mitigate the CD impact on the OCDMA system would therefore require addressing both, auto and cross correlation compensations.

To mitigate CD a number of CD compensation techniques have been demonstrated using dispersion shifting fibers (DSF) [5], fiber Bragg gratings (FBG) [6], planar lightwave circuits (PLC) [7], virtually imaged phased arrays (VIPA) [8], and arrayed waveguide gratings (AWG) [9]. These techniques are based on different approaches:

- PLC technique uses a thermo-optic phase control consisting of Mach-Zehnder interferometers [7].
- In VIPA, a quadratic phase distribution is used to achieve dispersion compensation between -1006 ps/nm to +834 ps/nm.
- In AWG, a lens is deployed in the middle of a double-AWG structure and dispersion is controlled through the strength of the parabolic phase signature [9].

In a number of existing techniques the insertion loss poses limitations [8] or the compensation range is affected by an intra-channel third order dispersion [6].

A Semiconductor Optical Amplifier (SOA) was also investigated for the chromatic dispersion compensation (CDC) of a data transmission which uses a *single wavelength* as the data carrier [12]. The advantage of using SOA is that, it offers a convenient tunable approach to CD compensation [10-13]. The concept behind using an SOA for distorted OCDMA auto-correlation width adjustment is based on exploiting refractive index and gain changes in a biased SOA [12,14,15]. Such changes can be introduced by a variety of ways:

- by varying the SOA bias current,
- through an SOA gain depletion,
- by injecting an optical continuous wave (cw) called continuous wave holding beam (CW/HB) together with data

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signal at the SOA input or

- by using an optical pulse stream called an Optical Pulse Holding Beam (for short OP/HB).

The above will result in SOA's refractive index changes [14]. Now, the interaction between the chirp triggered by these SOA changes and the incoming data pulses affected by CD can be exploited for managing CD effects [16].

To the best of our knowledge, we report for the first time an experimental investigation of the possibility of using SOA to mitigate the effect of CD on the 2D-WH/TS OCDMA auto-correlation width resulted from decoding two-dimensional wavelength-hopping time-spreading (2D-WH/TS) codes based on picosecond *multi-wavelength* carriers. The approach was applied to the recovered OCDMA auto-correlation of an incoherent OCDMA system based on two dimensional wavelength-hopping time-spreading codes, with 8 ps multi-wavelength pulses as code carriers.

II. Experimental Setup

A 17 km-long OCDMA testbed as shown in Fig. 1 was used to study the effectiveness of an SOA for simultaneous multi-wavelength CD compensation. This was for the transmission of an incoherent OCDMA system based on short multi-wavelength code carriers (four wavelengths, each pulse featuring 8 ps Full Width at Half Maximum (FWHM)).

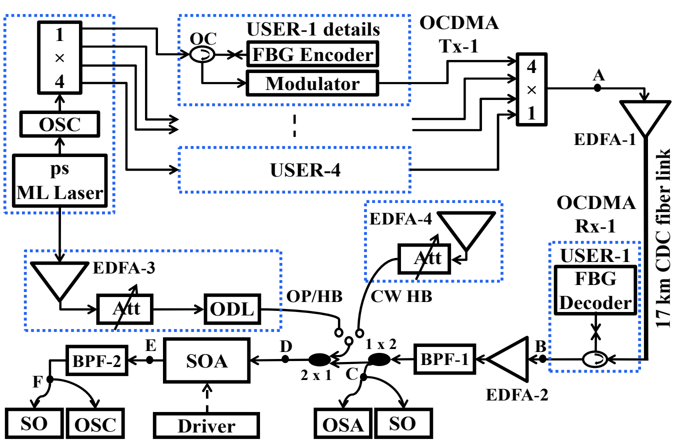


Fig. 1. OCDMA testbed to evaluate SOA CDC capabilities, OSC-optical supercontinuum, OC-optical circulator, EDFA-erbium doped fiber amplifier, BPF-tunable bandpass filter, SOA-semiconductor optical amplifier, OSA-optical spectrum analyzer, SO-sampling oscilloscope, ODL-optical delay line, Att-optical attenuator, ps ML Laser-picosecond erbium doped fiber mode-locked laser, CW HB-continuous wave holding beam, OP/BH-optical pulse holding beam.

The data traffic was generated by four OCDMA transmitters. After propagation in the testbed, it was presented to an OCDMA receiver which was matched to the USER-1 encoder, producing a code-weight four OCDMA auto-correlation peak. The OCDMA used 2D-(4,47) wavelength-hopping time-spreading (WH/TS) prime codes [21]. WH/TS prime codes is a class of two dimensional (2D: wavelength-time) incoherent (direct-detection), asynchronous codes that support wavelength hopping within time-spreading codes over Galois field of prime numbers with zero auto-correlation sidelobes (for ease of self-synchronization) and periodic cross-correlation functions of at most one (for minimal multiple-access interference) [21].

Each code consisted of four wavelength carriers based on a 100 GHz ITU grid; λ_1 = 1551.72 nm, λ_2 = 1550.92 nm, λ_3 = 1552.52nm, λ_4 = 1550.12 nm. These were positioned into 47 time chips (each of 8 ps duration) to create 2D-(4,47) WH/TS USER-1 to USER-4 codes. Wavelength carriers were generated by spectral slicing of a 3.2 nm wide optical supercontinuum (OSC). OSC resulted from a compression of a 1.8 ps FWHM laser pulse generated by an Erbium doped fiber mode-locked laser (MLL) (PriTel Inc.) running at 2.5 Gb/s. Using a 1×4 power splitter, OSC was supplied into four OCDMA code generators based on FBG encoders (OKI Industries, Japan) each producing a unique 2D-(4,47) WH/TS OCDMA code. Each code uses all four wavelengths by positioning them accordingly into chips. Chips occupied by the USER-1 through USER-4 codes are (1-λ_2, 21-λ_4, 24-λ_1, 39-λ_3); (1-λ_1, 17-λ_2, 31-λ_3, 47-λ_4); (1-λ_3, 11-λ_1, 29-λ_4, 37-λ_2) and (1-λ_4, 13-λ_3, 23-λ_2, 43-λ_1), respectively. Each code was then passed through the corresponding data modulator. Data traffic from all users was then combined by a 4 × 1 power combiner, re-amplified by an 18 dBm EDFA-1 and launched into a 17 km long bidirectional fiber link connecting The University of Strathclyde and Glasgow University. The link was then compensated for CD by using a commercially available dispersion compensating fiber module (DCM). The matching DCM was selected based on the testbed link length determined from OTDR measurements. Both, BPF-1 and BPF-2 are 3.2 nm wide tunable bandpass filters with central wavelength set to 1551.32 nm to ensure all four 2D-WH/TS OCDMA code wavelength carriers are passed, and block ASE from EDFA-2 and SOA, respectively.

III. Managing Compensation of OCDMA Auto-correlation by SOA

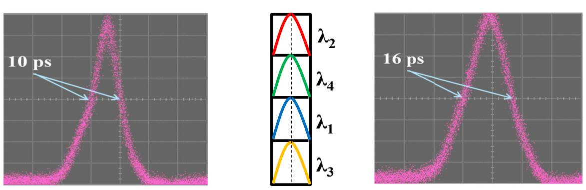
First we will discuss the operation of the SOA based compensation. SOA we used was Kamelian OPA-20-N-C with the gain recovery time τ_G = 75 ps. At the 2.5 Gb/s data rate, the User-1 auto-correlation peaks are separated by $\tau_{ACsepar}$ = 400 ps. The decoding of the User-1 own 2D-WT/TS code produces a User-1 auto-correlation with the code weight w (no auto-correlation side-lobes) and the cross-correlation bound to one (if also simultaneous users are transmitting) [21]. If USER-2 to USER-4 are also transmitting (i.e., the number of simultaneous users is N = 4), due to the User-1 decoding process the cross-correlation surrounding the decoded User-1 auto-correlation peak will be represented by 12 (w × (N-1)) codes carrier pulses separated from each other by $\tau_{CCsepar}$ ~T/12 = 33 ps (we have assumed an even cross-correlation spreading). Note that $\tau_{CCsepar}$ is much smaller than the SOA recovery (τ_G = 75 ps). Now, when the auto-correlation peak surrounded by the cross-correlation enters the SOA compensator, only the highest intensity auto-correlation peak can significantly influence the SOA gain dynamics via full or partial depletion of its gain.

Because the auto-correlation peaks separation $\tau_{ACsepar}$ = 400ps is greater than τ_G = 75 ps there is enough time for SOA to fully recover its gain before the next one arrives and the compensation can take place each time the auto-correlation passes the fully recovered SOA.

As indicated earlier, the separation between adjacent cross-correlation pulses $\tau_{CCsepar}$ ~ 33ps is much less than the SOA gain recovery τ_G = 75ps. Therefore to simultaneously compensate both, the auto and cross-correlation, SOA with a recovery time shorter than $\tau_{CCsepar}$ is needed. Ideally, SOA with $\tau_G < \tau_{chip}$, where τ_{chip} is the chip-width, would be desired.

Before starting our experimental investigation, to mimic the receiver relocation, we first introduced the 'residual level' of CD into the fiber-optic testbed by adding a few meters of FMS-28 optical fiber. Since no commercial equipment was available, the 'residual' level of CD was determined as follows:

- First the FWHM value Δ_{BB} of the OCDMA auto-correlation peak produced by the OCDMA USER-1 FBG decoder was determined from back-to-back measurements (case when OCDMA auto-correlation is not affected by CD). The results are shown in Fig. 2(a). Figure 2(b) illustrates that the OCDMA auto-correlation consists of all 4 wavelength pulses aligned by the FBG decoder to 'sit' on top of each other.
- Secondly, the FWHM value of the auto-correlation was measured after a 17 km long OCDMA data transmission to point C (see Fig. 1) with the CD compensation implemented. Prior to taking this measurement the signal was amplified by EDFA-2 and the recovered USER-1 OCDMA auto-correlation (spectral width 4 × 100 GHz) was then passed through a 3.2 nm band pass filter (BPF-1) with its center wavelength set to 1551.32 nm. The results obtained are shown in Fig. 2(c). All FWHM measurements were carried out using an Agilent Infiniium DCA-J 86100C equipped with a 64 GHz optical sampling head.



(a) (b) (c)

Fig. 2(a). OCDMA auto-correlation as seen at the OCDMA USER-1 decoder output for back-to-back measurements. FWHM value is Δ_{BB} = 10 ps; (b) the illustration of the OCDMA auto-correlation; (c) OCDMA auto-correlation after 17 km of propagation in a partially CD compensated fiber link. FWHM value is Δ = 16 ps. (Data were recorded by a sampling oscilloscope (SO), Agilent Infiniium DCA-J 86100C with a 64 GHz optical sampling head).

By comparing the results shown in Fig. 2(a) and Fig. 2(c), we found a 6 ps under-compensation of the transmission link. This value was then compared with results published in [2]. We concluded that the 6 ps broadening of the USER-1 OCDMA auto-correlation observed is due to the CD compensation mismatch which is equivalent in length to 66 m of SMF-28 fiber. To make the testbed 'fully' CD compensated this length would need to be deducted from the existing testbed length. Therefore, to account for this, we decided to determine if an SOA could be utilized for such compensation instead. This investigation was then performed for incoherent OCDMA transmission based on 2D-wavelength-hopping time-spreading codes with 8 ps multi-wavelength pulses as the code carriers.

A. Compensation by changing the SOA bias current (SOA gain) and by varying optical power of CW holding beam (CW/HB)

In this investigation, the OCDMA auto-correlation produced by the USER-1 decoder after a17 km propagation in the partially CD compensated fiber link was first amplified by EDFA-2. The OCDMA auto-correlation was then passed through a band pass filter (BPF-1). It was then injected into an SOA (Kamelian OPA-20-N-C with the gain recovery time τ_G = 75 ps) which was kept at a constant temperature of 20°C by a current-temperature controller. BPF-1 was used to reject the out-of-band ASE noise [17] produced by EDFA-2.

It was determined that an SOA bias current of I = 30 mA corresponds to an SOA gain G = 1 (0 dB), while I = 125 mA led to SOA gain saturation [12]. Figure 3(a) shows a parameter R as a function of SOA bias current I, where $R = \Delta_I / \Delta_{BB}$. Here Δ_{BB} = 10 ps is the measured FWHM value of the *back-to-back* OCDMA auto-correlation produced by the USER-1 OCDMA decoder (see Fig. 2(a)) and Δ_I is its value measured at point E after 17 km long transmission in the testbed with a 6 ps CD mismatch and the SOA bias current set to value I.

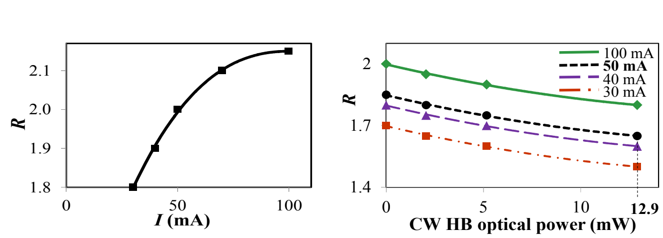
Let as now analyze the meaning of parameter R:

-When $\Delta_I = \Delta_{BB}$ the parameter $R = 1$, which means that the OCDMA auto-correlation width after passing the biased SOA has the same value as for the back-to-back measurements. This indicates that the effect of transmission link CD on the OCDMA auto-correlation has been compensated for by the SOA.

-When $R < 1$ then $\Delta_I < \Delta_{BB}$ at the SOA output and we will observe the compression as shown in Fig. 4.

-When $R > 1$ then $\Delta_I > \Delta_{BB}$ at the SOA output which indicates auto-correlation broadening by SOA as shown in Fig. 3.

In Fig. 3(a) we can see that $R \in (1.8 - 2.15)$. Value R = 1.8 corresponds to I = 30 mA and $\Delta_{I=30}$ = 18 ps, while R = 2.15 corresponding to I = 100 mA (SOA's saturation point) leads to $\Delta_{I=100}$ = 21.5 ps. Our experimental results agree with the



(a) (b)

Fig. 3(a). Coefficient R vs SOA bias current I – no ASE from EDFA-2; (b) Coefficient R vs CW/HB optical power, case of four different SOA bias currents I when ASE from EDFA-2 was not present. (Point I = 50 mA and CW/HB optical power of 12.9 mW is indicated for cross referencing).

theory presented in [18] where the pulse spectrum changes due to self-phase modulation (SPM) via nonlinear refractive index changes introduced by SOA bias current variations, i.e., SOA gain and in turn the SPM induced chirp affects the SOA traversing USER-1 OCDMA auto-correlation. Results shown in Fig. 3(a) clearly show the auto-correlation FWHM broadening with an increasing SOA drive current, i.e., gain.

Next we introduced a CW Holding Beam (CW/HB) generated by an 18 dBm EDFA (EDFA-4 in Fig. 1) to investigate how the coefficient 'R' changes with different values of SOA bias current 'I' at the presence of different optical power levels of the CW/HB. The results are shown in Fig. 3(b). Greater compression, smaller R values, $R \in (1.5 - 2.0)$, are observed with the presence of increasing CW/HB optical power than without CW/HB, $R \in (1.8 - 2.15)$.

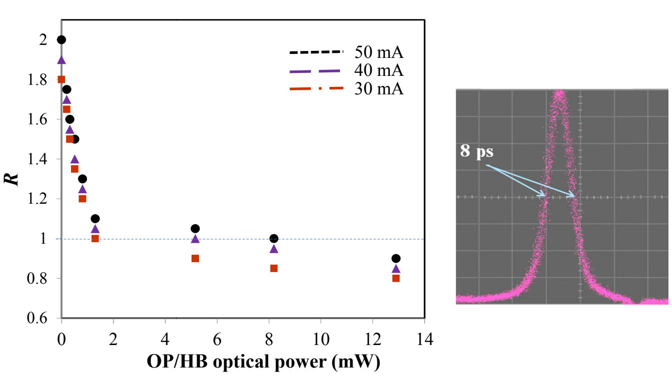
B. Compensation by varying the optical power of OP/HB

To exploit the gain dynamics of the SOA we have investigated how the presence of a short Optical Pulse as the Holding Beam (*OP/HB)* affects the SOA's ability to modify CD. Based on availability, for OP/HB we used optical pulses ($\lambda_{OP/HB}$ = 1545 nm, 2 ps FWHM) generated by the ML laser (see Fig. 1). Both, BPF-1 and BPF-2 are 3.2 nm wide tunable bandpass filters with central wavelength set to 1551.32 nm to ensure that all four 2D-WH/TS code wavelength carriers are passed, but ASE from EDFA-2, and $\lambda_{OP/HB}$ on the SOA output are blocked. OP/HB was injected into SOA in line with the USER-1 OCDMA auto-correlation via an optical delay line (ODL) set to produce a 0 ps relative delay between them. The varying OP/HB optical power via an optical attenuator, Att (Agilent 8156A, Fig. 1) changes the value of R. The results are shown in Fig. 4(a). The full CD compensation by SOA (R = 1) was observed for one of the following settings:

- OP/HB optical power 1.3 mW and I = 30 mA;
- OP/HB optical power 5.16 mW and I = 40 mA;
- OP/HB optical power 8.19 mW and I = 50 mA.

A maximum achieved compression by SOA (R_{min} = 0.8) resulted in FWHM $\Delta_I = 8$ps (Fig. 4(b)) for the following setting:

- OP/HB power level 12.9 mW and I = 30 mA.



(a) (b)

Fig. 4(a). Coefficient R vs OP/HB optical power for four different SOA bias currents - case when ASE from EDFA-2 is not present; (b) Example of OCDMA auto-correlation for R_{min} = 0.8 (FWHM $\Delta_{I=30}$ = 8 ps) measured at USER-1 decoder output after 17 km of propagation in a partially CD compensated fiber link with the implemented SOA compression technique when using OP/HB optical power 12.9 mW and SOA bias current I = 30 mA.

C. Compensation by varying the optical power of OP/HB in the presence of ASE

Next, we investigated how the presence of ASE at the SOA input affects the ability of the OP/HB to vary CDC.

Again, 2 ps FWHM optical pulses from the ML Laser as OP/HB (see Fig. 1) were combined with ASE from EDFA-2 (BPF-1 was removed at the EDFA-2 output, Fig. 1) and then injected into the SOA together with the USER-1 OCDMA auto-correlation via the optical delay line (ODL).

The values of R obtained vs the OP/HB optical power for different SOA bias currents I are shown in Fig. 5. It can be seen that, for a given OP/HB optical power, lower R values are achieved for lower SOA bias currents, i.e. lower gain.

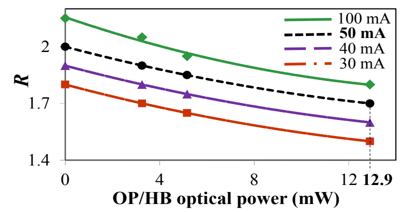


Fig. 5. Coefficient R vs OP/HB optical power for four different SOA bias currents I when ASE from EDFA-2 was present. (Point I = 50 mA and OP/HB optical power of 12.9 mW is indicated for cross referencing).

By comparing the results obtained, $R \in (0.8, 2.1)$ in Fig. 4(a) with $R \in (1.5, 2.1)$ in Fig. 5, it can be concluded that the presence of ASE limits the ability of the OP/HB to achieve the OCDMA auto-correlation compression (values R < 1) observed without ASE. This agrees well with [17] for a single wavelength compensation investigation.

In the absence of ASE, the SOA traversing OCDMA auto-correlation experiences a red shift of its leading edge (negative chirp) while a negligible blue shift (positive chirp) is imposed over its trailing edge. This leads to a stronger-in-average negative chirp if compared to the case when ASE is present. In other words, compression will increase with increasing negative chirp [16]. The presence of ASE slightly reduces the amount of red shift (negative chirp) at the leading edge but significantly increases the blue shift (positive chirp) of its trailing edge due to the ASE-induced SOA recovery speed-up. The net result is a predominantly linear chirp across the central part of the OCDMA auto-correlation. All of the above indicate that the SOA produces a more negative chirp in the 'absence of ASE' at its input than in the 'presence of ASE' and therefore more compensation (smaller R) is possible. In addition, the narrower the OP/HB pulses are (steeper the leading edge) the more 'instantaneous' the SOA gain change becomes and as such, a larger value of compression can be achieved. The use of SOA for CDC will also positively mitigate the influence of multi access interference from the other encoders as was shown in [19].

D. Relative delay role between OP/HB and auto-correlation

The position of OP/HB relative to the USER-1 OCDMA auto-correlation peak at the entry point of SOA was investigated in the presence of ASE. The ODL (Fig. 1) was used for delay adjustments. The results obtained are shown in Fig. 6. It can be seen that more compression (i.e. smallest *R*) was achieved when OP/HB entering the SOA was overlapped with the USER-1 OCDMA auto-correlation peak (0 ps delay). This is because the combined optical peak power from both overlapping pulses (relative delay equal to zero) maximizes the SOA gain depletion, and thus creates preferred conditions for the compression by SOA.

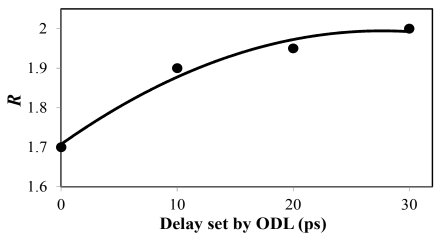


Fig. 6. Coefficient R vs relative delay between OP/HB and the USER-1 OCDMA auto-correlation, case when I = 50 mA, OP/HB optical power was 12.9 mW and ASE from EDFA-2 was present (no BPF-1 present).

In addition, instead of using a locally generated OP/HB for controlling the SOA gain dynamics, an all-optical clock recovery from the incoming OCDMA traffic [20] can be implemented for OP/HB generation. This will also help to eliminate a possible timing jitter between locally generated OP/BH and recovered OCDMA auto-correlation.

IV. Conclusion

We have investigated the SOA for its use to compensate the OCDMA auto-correlation broadening/skewing due to the fiber link chromatic dispersion. Our investigation was applied to an incoherent OCDMA transmission system based on 2D-(4,47) WH/TS OCDMA codes with *multi-wavelength picosecond pulses* as code carriers. The results were obtained for different SOA control parameters: (1) varying drive current, (2) changing the power of CW and optical pulses used as holding beams (CW/HB and OP/HB), (3) presence of ASE from EDFA at SOA input, and (4) the role of a relative delay between OP/HB and the OCDMA auto-correlation at the SOA input. We have also shown that if the compensation is applied directly to the recovered OCDMA auto-correlation, only a single control pulse per the data bit is needed to simultaneously affect all four wavelength code carriers. To conduct our investigations we used a 17 km long fiber-optic testbed connecting The University of Strathclyde and Glasgow University. We have shown that the back-to-back 10 ps FWHM OCDMA auto-correlation *composed of multi-wavelength* picosecond code carriers, when distorted by a 17 km long propagation in the partially compensated fiber optic testbed, can be either compressed down to or further broadened to values between 8 and 21 ps by controlling the SOA chirp. This makes the demonstrated SOA approach to OCDMA auto-correlation compensation an attractive option for implementation in incoherent OCDMA systems based on ps multi-wavelengths code carriers. To fully mitigate the impact of CD on the OCDMA system performance would also require addressing cross-correlation compensation by using SOA with its gain recovery time shorter than the chip-width.

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