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# Mitigation of Temperature Induced Dispersion in Optical Fiber on OCDMA Auto-correlation

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**Abstract**—We have experimentally investigated the influence of temperature on the OCDMA auto-correlation recovered after transmission in an optical fiber link when exposed to different temperature settings. The OCDMA system uses two dimensional wavelength-hopping time-spreading (2D-WH/TS) codes based on picosecond multi-wavelength pulses. To the best of our knowledge, we have confirmed for the first time experimentally that a recovered OCDMA auto-correlation will be affected by transmission link temperature changes. Our simulation results are in good agreement with experimental observations. We have also demonstrated that the observed auto-correlation width change can be mitigated by introducing a semiconductor optical amplifier as part of the OCDMA receiver.

**Index Terms** — OCDMA, OCDMA Auto-correlation, Semiconductor Optical Amplifier, Chromatic Dispersion, Temperature Induced Dispersion, Chirp, Fiber Transmission.

## I. INTRODUCTION

IN direct detection fiber communication systems employing short picosecond pulses as data carriers, compensation for fiber induced chromatic dispersion (CD) is required. Uncontrolled CD results in pulse-broadening, inter-symbol interference and can lead to a complete collapse of data transmission [1], [2]. Various methods have been investigated for chromatic dispersion compensation (CDC). Manual and automatic /tunable ways of realizing CDC have been considered [2-4]. For example, tunable dispersion compensation can be implemented by varying the chirp on fiber Bragg gratings with external perturbation [3]. The most common method to control CD is to use dispersion compensated fiber (DCF) [2]. The drawback of this approach is its rigidity. It requires a set of fiber spools of different lengths in the inventory to match varying network needs [2], [5]. In the case of high-data-rate systems when the data bit is very short (order of a few picoseconds) CD compensation is a ‘must’ and needs to be controlled with tight tolerances.

Fiber optic cables are buried at least 2-4 feet beneath the ground facing an average of 20 °C temperature variations [6]. In a number of countries fiber optic cables are carried on pools

above the ground where they are exposed to even higher temperature fluctuations [7]. As of today, there has been a very limited number of studies [2], [6-8] investigating the effects of temperature induced dispersion variations in optical fibers and how a high speed data communication and/or OCDMA based on picosecond multi-wavelengths data carriers will be affected. In [2], it has been reported that ON/OFF keying 40-Gb/s systems will require mitigation of temperature induced dispersion. In [8], it has been predicted that CD induced temporal skewing (consequently leading to auto-correlation broadening) has a strong detrimental effect on bit-error-rate (BER) of OCDMA systems with 2D-WH/TS codes using multi-wavelength picosecond pulses as their carriers. In [9] is shown that a CD imposed pulse broadening and resulted power penalty will limit the number of simultaneous users and degrade OCDMA system BER. Simulation results obtained in [5] indicate that fiber temperature changes can similarly affect the recovered OCDMA auto-correlation function and BER but no experiments were performed. In [10] and [11], it has been reported that Semiconductor Optical Amplifier (SOA) can be used to mitigate optical pulse width changes inflicted by the anomalous chromatic dispersion (CD) in optical fiber. In [10], a study of using SOA for CD mitigation in case of a single wavelength data carrier was demonstrated in a 17 km long SMF-28 based testbed. By varying the SOA bias current, both pulse compression and expansion between 20 ps to 25 ps of the original 23 ps optical pulse was achieved. In [11], combination of SOA bias current changes and injection of the optical holding beam at various power levels into SOA synchronously with a single wavelength data carrier were investigated to control the data carrier pulse width.

In this paper we report for the first time an experimental demonstration of fiber temperature induced effects on 2D-WH/TS OCDMA auto-correlation based on multi-wavelength picosecond pulses as code carriers and the mitigation of these effects by deploying a semiconductor optical amplifier (SOA) in the OCDMA receiver. The performed simulations are in good agreement with our experimental observations.

## II. EFFECT OF FIBER TEMPERATURE ON OCDMA AUTO-CORRELATION

There is a number of codes [12] developed to support a coherent OCDMA. The coding is done by manipulating the code carrier phase. An example would be Hadamard codes often referred to as Walsh Codes, Gold codes, and Kasami codes. Codes developed to support an incoherent OCDMA do not use the code carrier phase for coding. They are one-dimensional unipolar codes known as optical orthogonal

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codes, prime codes including 2D-WH/TS code. A 2D-WH/TS prime code is a class of two dimensional (2D: wavelength-time), incoherent (direct-detection), asynchronous codes that support wavelength-hopping within time-spreading over Galois field of prime numbers with zero auto-correlation side-lobes (for ease of self-synchronization) and periodic cross-correlation functions of at most one (for minimal multiple-access interference). They offer good cardinality and can support a large number of simultaneous users. 2D-WH/TS OCDMA codes usually occupy only a small portion of the fiber spectrum. They usually use a set of few picoseconds

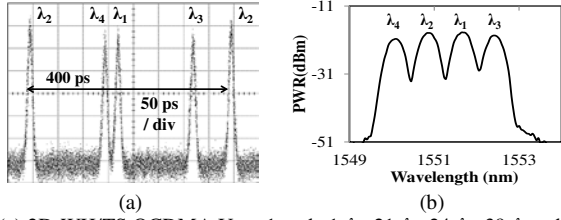


Fig. 1(a) 2D-WH/TS OCDMA User-1 code 1- $\lambda_2$ , 21- $\lambda_4$ , 24- $\lambda_1$ , 39- $\lambda_3$ ; where,  $\lambda_1 = 1551.72$  nm,  $\lambda_2 = 1550.92$  nm,  $\lambda_3 = 1552.52$  nm, and  $\lambda_4 = 1550.12$  nm. The code length is 400 ps; (b) optical spectrum occupied by the code.

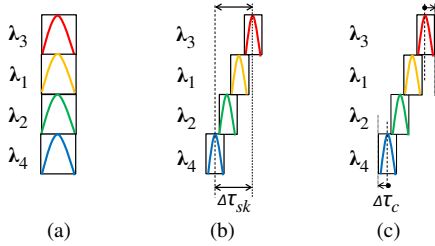


Fig. 2(a) Unaffected 2D-WH/TS OCDMA auto-correlation ( $\lambda_i$  are code carrier,  $\lambda_4 < \lambda_2 < \lambda_1 < \lambda_3$ ); (b) Illustration how the code carriers skewing influences the auto-correlation width; (c) Illustration how changed carriers' width also contributes to already skewed OCDMA auto-correlation width.

wide multi-wavelength pulses as code carriers. In this investigation we used four different wavelength carriers that occupied 3.2 nm of spectrum, see Fig. 1. Their temporal width will be affected by both, fiber chromatic dispersion and temperature induced dispersion. As a consequence, the recovered OCDMA auto-correlation will be broadened by changes in code carriers' temporal width and by their temporal skewing as is illustrated in Fig. 2. This effectively reduces the originally designed number of chips/bit i.e., a maximum number of simultaneous users with error-free BER [9], [12].

The temporal pulse width change of each code carrier  $\lambda_i$  due to the fiber CD can be expressed as  $\Delta\tau = D_{CD} \times \Delta\lambda_i \times L$  [8], [14].  $D_{CD}$  is the chromatic dispersion coefficient of the optical fiber link ( $D_{CD} = 17$  ps/nm•km for SMF-28),  $\Delta\lambda_i$  is the code carrier's spectral width and  $L$  is the propagation distance. When the transmission link is fully CD compensated, we can assume  $\Delta\tau = 0$  and therefore no code carrier's broadening due to fiber chromatic dispersion is observed and no OCDMA auto-correlation distortion due to temporal skewing will take place. However, if the temperature of the CD compensated transmission link changes by  $\Delta T$ , the temperature induced fiber link dispersion  $D_T$  will come into play and will induce a pulse width change  $\Delta\tau_i$  on each wavelength code carrier  $\lambda_i$ .

$$\begin{aligned} \Delta\tau_i &= D_T \times L \times \Delta\lambda_i \times \Delta T \\ &= (D_{T-SMF} \times L_{SMF} + D_{T-DCF} \times L_{DCF}) \times \Delta\lambda_i \times \Delta T \end{aligned} \quad (1)$$

For the SMF-28 fiber the temperature induced dispersion coefficient  $D_{T-SMF} = -0.0016$  ps/nm•km/°C, for DCF fiber  $D_{T-DCF} = +0.004$  ps/nm•km/°C [15] and  $L_{SMF}$  ( $L_{DCF}$ ) is the corresponding fiber length, respectively. It is worth noting that the temperature induced dispersion coefficient for SMF-28 has an opposite sign when compared to  $D_{CD}$ .

In our investigations the four code carriers are spectrally adjacent (see Fig. 1(b)) and also have the same spectral width  $\Delta\lambda_i = 0.8$  nm. Therefore the total spectrum the 2D-WH/TS OCDMA code and related auto-correlation occupy is

$$\Delta\lambda = \Delta\lambda_i \times w = 0.8 \times 4 = 3.2 \text{ nm} \quad (2)$$

where  $w = 4$  is the number of wavelength (code carriers) used by the 2D-WH/TS code;  $w$  is also known as the code weight.

Due to a temperature induced dispersion, each code carrier travels at a different speed  $v_i$ . When resulting fiber link  $D_T < 0$  and  $\lambda_4 < \lambda_2 < \lambda_1 < \lambda_3$  (see Fig. 1(b)) then  $v_{\lambda_4} < v_{\lambda_2} < v_{\lambda_1} < v_{\lambda_3}$ . Because of differences in carriers' arrival times, at the fiber receiving end, the recovered OCDMA auto-correlation width will be affected firstly, by the temporal skewing  $\Delta\tau_{sk}$  between code carriers. This is illustrated in Fig. 2(b). The amount of  $\Delta\tau_{sk}$  is decided by skewing between code carriers with the lowest and the highest speed (i.e.,  $\lambda_4$  and  $\lambda_3$ , respectively - see Fig. 2(b)). Secondly, because the code carriers' linewidth  $\Delta\lambda_i$  is not infinitely narrow, their temporal width will also change thus additionally contribute to the width change of the already skewed OCDMA auto-correlation. This contribution can be estimated as  $\Delta\tau_c$  (see Fig. 2(c)). The contribution from both these effects can be expressed as

$$\Delta\tau_T = \Delta\tau_{sk} + 2 \times \Delta\tau_c \quad (3)$$

If we now approximate code carriers' temporal shape as being rectangular and follow illustrations in Fig. 2 we get

$$\Delta\tau_{sk} = D_T \times \Delta\lambda_i \times (w - 1) \times L \times \Delta T \quad (4)$$

For  $\Delta\tau_c$  the following expression can be derived

$$\Delta\tau_c = D_T \times L \times \Delta T \times \Delta\lambda_i / 2 \quad (5)$$

and by substituting Eq. 2, Eq. 4, and Eq. 5 into Eq. 3 we get

$$\Delta\tau_T = D_T \times \Delta\lambda \times L \times \Delta T \quad (6)$$

This simplified approximation would allow us to estimate a scenario when DCF is kept at a constant temperature ( $D_{T-DCF} = 0$ ) and only SMF-28 is exposed to a temperature change. After considering values  $D_T = D_{T-SMF} = -0.0016$  ps/nm•km/°C,  $\Delta\lambda = 3.2$  nm, transmission distance  $L = 19.5$  km, and the fiber transmission link temperature change  $\Delta T = 30$  °C, the estimated numerical value for the OCDMA auto-correlation broadening using this simplified rectangular temporal code carriers' envelope shape is  $\Delta\tau_T \sim 3$  ps. We would later see that the experimentally measured  $\Delta\tau_T$  value was  $\sim 1$  ps.

A more accurate approximation for  $\Delta\tau_T$  can be obtained by assuming a Gaussian shape of the OCDMA multi-wavelength code carrier pulses. Based on [5] and by realizing that in this investigation a  $\Delta\lambda_i$  linewidth of each wavelength code carrier is equal to a code carrier's spectral separation  $\Delta\lambda_i$ , the temperature dependent OCDMA auto-correlation envelope  $S_T^L(t)$  can be represented by:

$$S_T^L(t) = \sum_{k=0}^{w-1} P_0 \exp \left\{ -2.77 \left[ \frac{t-k \Delta\tau_{Ti}}{\tau - \Delta\tau_{Ti}} \right]^2 \right\} \quad (7)$$

where  $P_0 = P(L = 0, \Delta T = 0) = 1$  is the wavelength code carrier normalized peak power and  $\Delta\tau_T$  is given by Eq. (1). By using a measured temporal width of each wavelength code carrier at 20 °C,  $\tau = 12$  ps,  $D_{T-SMF} = -0.0016$  ps/nm•km/°C,  $D_{T-DCF} = +0.004$  ps/nm•km/°C, temperature change  $\Delta T = 30$  °C,  $L_{SMF} = 19.5$  km,  $L_{DCF} = 3.32$  km,  $\Delta\lambda_i = 0.8$  nm,  $\Delta\lambda_i = 0.8$  nm, three scenarios were investigated. Results for  $S_T^L(t)$  were plotted in Fig. 3: (a) the fully CD compensated link (i.e., SMF-28 + DCF) at  $T = 20$  °C; (b) SMF-28 + DCF at  $T = 50$  °C; (c) SMF-28 at  $T = 50$  °C but DCF at  $T = 20$  °C. By analyzing the simulation results of the OCDMA auto-correlation FWHM change, one can conclude: (a) There is no auto-correlation width change for a CD compensated link kept at the constant temperature. (b) A 0.5 ps width broadening from 12 ps to 12.5 ps for a 30°C temperature increase of an entire transmission link. (c) A 0.9 ps width broadening from 12 ps to 12.9 ps for a 30°C temperature increase of the SMF-28 fiber section only (DCF is kept at a room temperature).

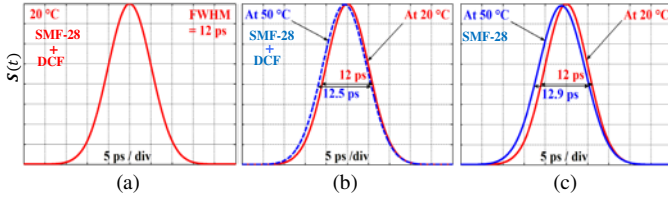


Fig. 3(a) Unaffected OCDMA auto-correlation envelope  $S(t)$  after code transmission in the CD compensated fiber link at 20 °C; (b) after raising link temperature to 50 °C; (c) when only SMF-28 section is heated to 50 °C and DCF section is kept at 20 °C.

### III. EXPERIMENTAL SETUP

The experimental setup used for this investigation is shown in Fig. 4. It consists of an OCDMA transmitter, OCDMA receiver, environmental chamber, 19.5 km of SMF-28 optical fiber on a spool, chromatic dispersion compensating fiber (DCF), and diagnostic equipment. Both OCDMA transmitter and receiver are based on fiber Bragg grating (FBG) technology. An integral part of the OCDMA transmitter was an optical supercontinuum generator (OSCG) producing a 3.2 nm wide optical supercontinuum. The supercontinuum was fed into an FBG OCDMA encoder (OKI Industries, Japan) for generation of a 2D-WHTS OCDMA code. The code consisted

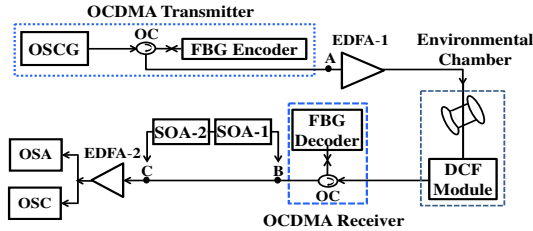


Fig. 4. Experimental setup; OSCG - Optical Supercontinuum Generation, OC - Optical Circulator, EDFA - Erbium Doped Fiber Amplifier, DCF - Dispersion Compensating Fiber, SOA - Semiconductor Optical Amplifier, OSC - Oscilloscope, OSA - Optical Spectrum Analyzer.

of four wavelength code carriers ( $\lambda_1 = 1551.72$  nm,  $\lambda_2 = 1550.92$  nm,  $\lambda_3 = 1552.52$  nm, and  $\lambda_4 = 1550.12$  nm). After its amplification by a 15 dBm EDFA-1, the code was launched into a fiber transmission link represented by a 19.5 km long SMF-28 fiber followed by a 3.32 km long DCF fiber for the link DC compensation. During our investigations the

temperature of the link (or its portion) was varied between 20 °C (room temperature) and 50 °C using an environmental chamber (SM-32C from Thermatron Industries).

In order to separate CD effects from the temperature induced dispersion effects, the transmission link was fully CD compensated with the sub-picosecond accuracy by using a matching dispersion compensating fiber module (DCF).

On the receiving site, the received OCDMA signal was decoded by a matched FBG-based OCDMA decoder. This produced an OCDMA auto-correlation, which was amplified by EDFA-2. The auto-correlation was then evaluated by an Oscilloscope, OSC (Agilent Infiniium DCA-J 86100C with an optical sampling head) and Optical Spectrum Analyzer (OSA).

### IV. INVESTIGATION OF FIBER TRANSMISSION LINK TEMPERATURE EFFECTS ON OCDMA AUTO-CORRELATION

First the environmental chamber holding transmission fiber was set to match the room temperature (20 °C). For future reference, the OCDMA auto-correlation  $S_T^L(t)$  was then recorded by OSC using the experimental setup shown in Fig. 4, no SOAs were present. The experimental result is shown in Fig. 5(a) in black. For a comparison, the simulation result from Fig. 3(a) in black. For a comparison, the simulation result from Fig. 3(a) is overlaid (red line). Then the environmental chamber temperature was increased to 50 °C with SMF-28 section only, DCF section was kept at 20 °C. After reaching a steady state (after ~ 4 hours), the OCDMA auto-correlation was recorded. The experimental result is shown in black in Fig. 5(b). For a comparison, the simulation result from Fig. 3(c) is overlaid (blue line). We can see that the amount of auto-correlation broadening  $\Delta\tau_T = 1$ ps is in a very good agreement with a 0.9 ps value predicted by our simulations. Misalignments observed at the pulses base are due to a minor FBG encoder/decoder miss-match resulted from manufacturing imperfections. Because of the setup resolution, we were unable to experimentally confirm the simulation results shown in Fig. 3(b) predicting the  $\Delta\tau_T = 0.5$  ps auto-correlation broadening.

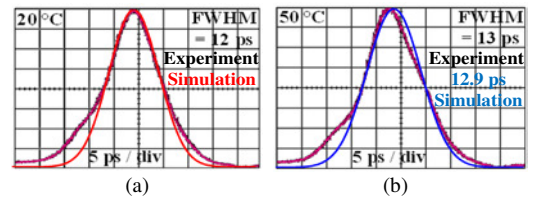


Fig. 5(a) OCDMA auto-correlation when CD compensated transmission link is at 20 °C: black - experiment, red - simulation; (b) when SMF-28 section is at 50 °C and DCF at 20 °C: black - experiment, blue - simulation.

The effect of the temperature can be explained as follows. The SMF-28 fiber produces the anomalous chromatic dispersion ( $D_{CD} > 0$ ) leading to the negative chirp  $C < 0$ . By adding a matching length of the dispersion compensating fiber (DCF has a normal chromatic dispersion,  $D < 0$ ), the fiber transmission link becomes CD compensated. From this point on, a fiber temperature change (introduces  $D_T < 0$ ) will “flip” the overall transmission link dispersion balance towards the normal dispersion. The normal dispersion leads to a positive chirp  $C > 0$ , and a lower group velocity for higher-frequency components. This means the leading edge components of optical pulses travel slower than the rest of the pulse, the

trailing edge components travel faster and as a whole, the temporal width of each optical pulse becomes narrower. This way all four multi-wavelength code carriers  $\lambda_i$  are affected. In addition, code carriers with the longer wavelength will travel faster than those with the shorter wavelength. This causes their temporal skewing leading to OCDMA auto-correlation temporal broadening with any fiber temperature increase.

To experimentally study a possibility of using an SOA to mitigate the effects of temperature induced dispersion ( $D_T < 0$ ), an SOA (Kamelian OPA-20-N-C) was inserted between points B and C in the experimental setup (see SOA1 in Fig. 4). We then investigated if by changing the SOA1 gain/bias current it would be possible to eliminate the observed temporal change of the OCDMA auto-correlation width caused by the temperature induced dispersion. We started the investigation by setting the temperature of the environmental chamber to 50 °C. At this temperature the recorded OCDMA auto-correlation FWHM was found to be 13 ps (see Fig. 6(a)). Now, by changing the bias current of SOA1 we tried to restore the OCDMA auto-correlation FWHM back to the value previously recorded at a room temperature of 20 °C (see Fig. 5(a)). By manipulating the bias current  $I$ , we observed that the auto-correlation width would broaden for  $I > 23$  mA. For  $I < 23$  mA, the auto-correlation was compressed. To allow for a better visualization, the resulting signal was then amplified by SOA2. The result is shown in Fig. 6(b). By comparing it with the recorded OCDMA auto-correlation taken at 20 °C shown in Fig. 5(a), one can conclude that both auto-correlations have a very similar shape and the measured FWHM value of 12 ps.

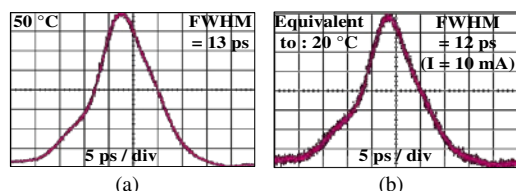


Fig. 6(a) OCDMA auto-correlation observed at 50 °C; (b) Adjusted OCDMA autocorrelation seen at 50 °C to its value measured at 20 °C;  $I = 10$  mA is the bias current of SOA1.


The above can be explained as follows: a pulse broadening by SOA will occur for pulses positively chirped ( $C > 0$ ) when transiting the SOA1 [13]. As discussed earlier, the temperature induced dispersion  $D_T$  in the fiber transmission link imposes a positive chirp ( $C > 0$ ) on optical pulses (OCDMA code carriers). This causes the additional skewing, therefore more broadening of the OCDMA auto-correlation when transiting the SOA1 at bias currents  $I > 23$  mA. At low SOA bias currents,  $I \ll 23$  mA (unsaturated gain), compression by the SOA is observed. Reducing the SOA bias current  $I$  to 10 mA changed the chirp value in the opposite direction leading to compression observed at the SOA-1 output [13]. SOA2 had no measurable effect on the passing auto-correlation other than amplifying the signal for its better detection.

## V. CONCLUSION

We study the effect of fiber temperature on the OCDMA auto-correlation when the temperature of a 22.8 km long CD compensated link or its SMF portion increases from 20 °C to 50 °C. The OCDMA system under investigation used 2D-

WH/TS codes based on multi-wavelength picosecond optical pulses as the code carriers. We have shown by simulations that the link 30 °C temperature increase will broaden the recovered OCDMA auto-correlation FWHM by a 0.5 ps from 12 ps to 12.5 ps. We have also experimentally demonstrated and then confirm by simulations that if this 30 °C temperature change is applied to its 19.5 km long SMF section, this will alter the FWHM value of the recovered OCDMA auto-correlation from 12 ps to 13 ps (12.9 ps when simulated). The measured 1 ps auto-correlation broadening is in a very good agreement with a 0.9 ps prediction which assumed a Gaussian temporal shape of code carriers. We also demonstrated that the SOA can be used to mitigate the observed amount of the broadening.

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