Chromatic dispersion monitoring and adaptive compensation using pilot symbols in an 8 x 12.5 Gbit/s all-optical OFDM system

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Abstract: We propose and experimentally demonstrate a novel technique for chromatic dispersion (CD) monitoring and adaptive compensation in an 8 x 12.5 Gbit/s all-optical orthogonal frequency-division multiplexing (AO-OFDM) system by using two pilot symbols and a virtually imaged phased array (VIPA) for a tunable CD compensator. The two pilot symbols are added to the first and the last sub-channels of the OFDM signal, and their relative time delay is detected and used for CD estimation at the CD monitoring circuit. The monitored CD value is fed to VIPA for CD compensation. In the experiments, the relative time delay between the two pilot symbols was successfully observed, and the adaptive CD compensation drastically improved the bit-error-rate (BER) from over 10⁻⁵ to under 10⁻⁹. The estimated CD values showed less than 10 ps/nm difference from the values measured by a photonic dispersion analyzer, which is accurate enough since the AO-OFDM system can keep BER<10⁻⁹ upto 20 ps/nm residual CD.

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1. Introduction

The increasing demand for new bandwidth-consuming applications is pushing the network operators and system vendors to increase the channel capacity, spectral efficiency, and the flexibility of optical networks. Orthogonal frequency division multiplexing (OFDM) is one of the most promising technologies for large capacity transmission and flexible network [1–9], and the all-optical (AO) implementation of discrete Fourier transform (DFT) and inverse DFT (IDFT) in the optical domain by using passive arrayed waveguide gratings and 10G-based electronics, can additionally reduce the energy consumption and the system costs [2–8]. In the previous experiments, we have successfully demonstrated an 8 x 12.5 Gbit/s AO-OFDM systems with a waveform reshaping scheme which enhance the system performance [10]. In addition, an optical packet switching (OPS) system of an 8 x 12.5 Gbit/s AO-OFDM with differential phase shift keying (DPSK) modulation format has been also demonstrated [11]. However, both experiments were performed in back-to-back (B-to-B) transmission, because chromatic dispersion (CD) seriously affects the sub-channel orthogonality, and therefore CD compensation is mandatory for an AO-OFDM transmission system over a fiber link. Figure 1 shows the schematics how the CD affects the orthogonality of the AO-OFDM system. In B-to-B transmission, all the sub-channels arrive the receiver AWG at the same time, and the perfect orthogonality is achieved at the center of symbol time slot after passing through the AWG, where only the target sub-channel can make intensity peak and the other sub-channels are cancelled, as shown in Fig. 1(a) [10]. On the other hand, in a standard single mode fiber (SSMF) link, CD causes not only a waveform distortion, but also a relative time delay among the sub-channels, so that the intensity peak of the target sub-channel no longer coincide with the null points of the other sub-channels, and it seriously break the orthogonality, as shown in Fig. 1(b) [12]. Therefore, CD compensation or CD tolerant system is mandatory to keep the orthogonality between sub-channels.

Fig. 1. The effect of chromatic dispersion on an AO-OFDM system. (a) Back-to-back and (b) SSMF transmission.
In a dynamic optical circuit or packet switched networks, perfect CD management is difficult to be achieved, due to the accumulation of the residual CD and dynamically changing unpredictable end-to-end transmission paths. In such dynamic optical switched networks, CD monitoring and adaptive CD management techniques are the key technologies for achieving optical OFDM-based flexible networks.

There are several methods to achieve a CD tolerant or CD compensated AO-OFDM system. Adding a cyclic prefix (CP) gives high tolerance to CD, although it sacrifices the effective data-rate due to the over-head. To tolerate a large amount of CD, the over-head become much longer, and the effective data-rate will be reduced. Moreover, it requires specially designed device to add the CP over-head in the optical domain [13], and therefore it is difficult to change the CP length adaptively according to the path length. Another way for CD management is to use an electrical digital signal processing (DSP). However, to apply a DSP for AO-OFDM system, high frequency sampling and analog-to-digital converter (ADC), and high performance processor are required, which are energy hungry devices. Therefore, to achieve an adaptive CD management with low power in AO-OFDM system, simple CD monitoring technique and tunable CD compensation are needed.

In this paper, we propose a novel CD monitoring technique in an AO-OFDM system, and demonstrate the adaptive CD compensation using a virtually imaged phased array (VIPA) as a tunable CD compensator [14]. We add pilot symbols to the first and the last sub-channels of an optical OFDM signal and evaluate their relative delay caused by CD. The monitored CD value is then fed to VIPA to compensate the CD. In the experiment, the bit-error-rate (BER) was drastically improved from over $10^{-5}$ to under $10^{-9}$ by the proposed method [15], and the monitored values were accurate enough to achieve the error free operation for different transmission length. The total performance (bandwidth and CD dynamic range) is limited by VIPA specification in this experiment. The dynamic range can be enhanced by cascading the tunable CD compensator, and the whole C-band can be covered by using a wide-band tunable CD compensation technique [16].

2. Operation principle and circuit configuration

Figure 2 shows the schematic of the proposed CD monitoring technique, where two pilot symbols are added to the first (ch1) and the last (ch8) sub-channels. Since the sub-channel spacing is 12.5 GHz, the wavelength difference of the two pilot symbols $\Delta \lambda$ is 0.7 nm (7 x 12.5 GHz). Having higher intensities than the payload, the pilot symbols can be easily extracted by thresholding operation. Figure 3 shows the CD monitoring circuit. In this circuit, ch1 and ch8 are de-multiplexed by the AWG that has the same configuration as the ones used in the AO-OFDM transmitter and receiver. The signal of ch1 is amplified and photo-detected, and the pilot symbol is extracted by thresholding operation in the limiting amplifier, then the signal is amplified again at the second stage electrical amplifier to drive an electro absorption modulator (EAM). The driving voltage amplitude is around 3-Vpp in the experiment. The signal of ch8 is sent to an EAM and the optical pilot symbol of ch8 is time gated by the electrical pilot symbol extracted from ch1. In this way, the output pulse indicates the overlapping duration of two pilot symbols, as illustrated in Fig. 3. The branches of ch1 and ch8 have timing offset of half duration of the pilot symbols, and therefore the output pulse width is half of the pilot symbols under the 0-CD condition. In this case, the CD monitoring circuit can monitor both positive and negative CD. The positive CD causes the decrease of the output pulse width due to the relative delay of ch8, whereas the negative CD causes the increase of the output pulse width due to the relative delay of ch1.

In this way, the pulse width of the gated pilot symbol extracted from ch8 represents the relative time delay $\Delta t$ between the two sub-channels, and the CD value $D$ [ps/nm] is estimated according to the definition of CD,

$$D = \frac{\Delta t}{\Delta \lambda}. \quad (1)$$
In this proof-of-concept experiment, the pulse width has been monitored using a sampling oscilloscope, but in an actual system, the total energy of the gated pilot symbol can be monitored by using an electrical low-pass filter and a level recognition circuit. In addition, because the pilot symbol is a wide pulse, which has 1.6 ns pulse width in the following experiments, all the electrical components do not have to be broad-band and it reduce the cost and power consumption. In the following experiments, the bandwidths of the electronic devices are around 10 GHz, but it could be lower depending on the pilot symbol length. The devices used for this circuit are a photo-receiver and an EAM, which are not special but standard devices and can be integrated all together for low cost. Moreover, an EAM can operate with low heating owing to its low driving voltage (~2V) and current. Therefore, the proposed circuit can be realized with low cost and low power consumption.

The pilot symbols are simple on-off-keying (OOK) pulse with almost no cross-talk (only these two channels exist at the timing of pilot symbols). This fact means that the pilot symbol is more robust to the channel impairments, such as optical signal-to-noise ratio (OSNR) degradation or frequency mismatch between the light source and the AWG [10], compared to the optical OFDM signal itself. Therefore, the proposed scheme has enough robustness for monitoring the CD in AO-OFDM systems.

3. Experimental demonstration

Figure 4 shows the experimental setup of an 8 x 12.5 Gbit/s AO-OFDM system with adaptive CD compensation. The optical comb for eight sub-channels with 12.5 GHz frequency spacing is generated from a continuous wave (CW) light source using two cascaded EAMs driven by 25 GHz and 12.5 GHz clock signals, respectively. The generated optical comb is split into two by a 3 dB coupler, and one is used to generate the optical OFDM signal, and the other one is used to generate the pilot symbols. To generate the optical OFDM signal, the pulse train is split into two again and modulated by 12.5 Gbit/s DPSK data sequences using LiNbO3 phase modulators (LN-PMs), respectively. The data pattern applied to the even and odd channels are independent 18688-bit sequences extracted from a 231-1 pseudo random binary sequence (PRBS). Each modulated data signal is split into four branches and sent to the AWG to perform IDFT. Each branch has a different delay line for pattern de-correlation. After the AWG, the optical OFDM signal is converted to a sequence of data packets using an LN
intensity modulator (IM) driven by a packet envelope signal, which consists of a 4160-bit payload and a 512-bit inter packet gap. The generated optical OFDM packet is then combined with the pilot symbols, which are composed of 20-bit of “1” sequences on ch1 and ch8 with 9dB higher intensity than the payload (see the inset of Fig. 4).

The waveform of optical OFDM signal is reshaped by another LN-IM to enhance the frequency orthogonality [8], and the optical OFDM packets are then transmitted through SSMFs with different lengths (5, 10, 15, 25, and 30 km). After the transmission, the CD is monitored by using the circuit in Fig. 3, and the monitored CD values are manually fed to VIPA for CD compensation. Then, the optical OFDM signal is sent to the receiver AWG to perform DFT operation for de-multiplexing. After the AWG, time gating is applied through an EAM driven by the clock signal to extract the center of symbol time slot of the signal. Finally, the signal is demodulated and detected using a Mach-Zehnder delayed interferometer (MZDI) and a balanced photo-receiver (BPR), and the system performances are evaluated by using a BER tester (BERT).

Figure 5 shows the waveforms of transmitted signal and the spectrum of optical OFDM signal with pilot symbols. The pilot symbols are added to ch1 and ch8 and they have higher intensity than the payload, as shown in Figs. 5(a) and 5(b). The guard time between the pilot symbols and payload is around 10 ns. Figures 5(c) and 5(d) show the waveform and spectrum of the multiplexed optical OFDM packet with two pilot symbols, respectively. After multiplexing all the sub-channels, the intensity of the payload and pilot symbols are almost same, and therefore the high intensity pilot symbols do not induce any penalty to the payload. Figure 6 shows the measured waveforms of the gated pilot symbols in the CD monitoring circuit. The variation of the pulse width has been successfully observed, which is proportional to the fiber lengths. The CD values have been estimated by substituting the monitored time delay into Eq. (1), and then compared to the values measured by a photonic dispersion analyzer. Table 1 reports the fiber length, monitored delay time, estimated and measured CD values. The estimated values show a very good agreement with the measured values with less than 10 ps/nm difference, so that the proposed technique is very effective to monitor the CD values.

![Experimental setup](image_url)
Fig. 5. The waveforms of transmitted signals of (a) only ch1, (b) only ch8, and (c) all sub-
channel multiplexed, and (d) the spectrum of optical OFDM signal with pilot symbols.

Fig. 6. Output signal from the CD monitoring circuit for different fiber length.

Table 1. Monitored Delay, Estimated and Measured CD values for different fiber length.

| Fiber length [km] | 5.03 | 9.84 | 14.87 | 25.00 | 30.56 |
|-------------------|------|------|-------|-------|-------|
| Monitored delay [ps] | 62.5 | 115.3 | 176.0 | 292.7 | 353.9 |
| Estimated CD [ps/nm] | 89.3 | 164.7 | 251.4 | 418.2 | 505.6 |
| Measured CD [ps/nm] | 83.5 | 165.0 | 248.5 | 418.0 | 503.3 |

The monitored CD values are manually fed to VIPA for the adaptive CD compensation, and we have measured the waveforms and the BERs of the received signals with and without the adaptive CD compensation. Figure 7 shows the eye-diagrams of the received signals after transmission over 5, 15, and 25 km of SSMFs with and without the adaptive CD compensation. The eye is seriously degraded even after 5 km transmission without the adaptive CD compensation, and there is almost no eye-opening after 25 km transmission. On the other hand, the eyes keep a clear opening owing to the adaptive CD compensation, as shown in the upper-side of Fig. 7. Figure 8 shows the measured BERs of the received optical OFDM signals. Without CD compensation, only 5 km transmission seriously degrades the BER up to $10^{-5}$, and the BERs corresponding to 25 and 30 km transmission could not be even measured. On the other hand, the adaptive CD compensation with the proposed CD monitoring technique drastically improves the BER and the performances are almost same as B-to-B transmission. These results show that the proposed adaptive CD compensation technique is very effective and essential for the AO-OFDM transmission systems.

We have also investigated the robustness of the AO-OFDM system to CD. In other words, we investigated how precisely the CD should be monitored and compensated. Figure 9 shows the measured BER as a function of the CD value without CD compensation. We see that the residual CD should be less than 20 ps/nm to keep the BER under $10^{-9}$. Since the monitored CD values show less than 10 ps/nm differences from the measured values, as aforementioned, the proposed CD monitoring scheme is accurate enough for error free performance of the system.

We have demonstrated the CD monitoring and adoptive compensation up to the CD value of 500 ps/nm for 100 Gbit/s AO-OFDM system. The main reason of the limitation is the pilot
symbol length and the specification of VIPA. The maximum delay for CD monitor is limited by the pilot symbol length, 1.6 ns (= 20-bit) in this case, and it corresponds to the CD value of over 2200 ps/nm. The maximum CD compensation with VIPA is 600 ps/nm and the bandwidth is limited to 120 GHz as specification. If we use a cascading of VIPA or wide-band and -range tunable CD compensation scheme [12], the dynamic range and total performance of the adaptive compensation becomes much better.

![Waveforms of the received signals](image1.png)

Fig. 7. Waveforms of the received signals for transmission distance of (a) 5km, (b) 15km, and (c) 25km, w/ and w/o adaptive CD compensation.

![Measured BERs](image2.png)

Fig. 8. Measured BERs for each transmission distance w/ and w/o adaptive CD compensation.

![Measured BER as a function of CD](image3.png)

Fig. 9. Measured BER as a function of CD.
4. Summary

We have proposed and experimentally demonstrated a novel CD monitoring and adaptive compensation technique for AO-OFDM systems. Pilot symbols are added to the first and the last sub-channels, and their relative time delay after the transmission gives an estimation of the CD value. The relative time delay of the pilot symbols was successfully observed by the proposed technique, and the BER was drastically improved from over $10^{-5}$ to under $10^{-9}$ by the adaptive CD compensation with the monitored CD value and VIPA. The estimated CD values showed a good agreement with those measured by a photonic dispersion analyzer with less than 10 ps/nm difference, which is accurate enough since the AO-OFDM system can keep error free operation (BER<$10^{-9}$) within the residual CD of less than 20 ps/nm. We believe that our proposed technique is very effective for the AO-OFDM transmission systems, especially for optical OFDM-based circuit or packet switched flexible networks, where the end-to-end CD management is rather difficult. The main limitation of this method is the pilot symbol length and VIPA specification. The CD value over 2200 ps/nm can be monitored by using 1.6 ns pilot symbols. VIPA can compensate CD up to 600 ps/nm, and the bandwidth is limited to 120 GHz. If we use better CD compensation technique with wide-band and -range, the dynamic range of adaptive compensation would be much larger over the whole C-band.