Performance Evaluation of All-Optical OFDM System- Based Optical Frequency Comb Source

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Abstract

In this paper, design and investigation of all-optical orthogonal frequency division multiplexing (AO-OFMD) system using an optical frequency comb (OFC) source is presented. An OFC source by cascading a frequency modulator (FM) and two intensity modulators is used as a multi-carrier’s generator to provide optically OFDM subcarriers. This OFC source can be provided a maximum comb lines number of 61 lines spaced by 25 GHz. The AO-OFDM scheme employed 31 and 51 comb lines can transmit a signal at a data rate of 1.55 and 2.55 Tbit/s, respectively. Numerical results are carried out using VPI transmission Maker® commercial software.

Keywords : All-optical OFDM, Terabit per second (Tbit/s), Optical frequency comb source, Error vector magnitude (EVM), Eye diagram

I. Introduction

Orthogonal frequency division multiplexing (OFDM) is a successful technology for high-speed wireless systems, such as WiMAX, third generation, and fourth-generation cellular wireless networks [I-IV]. This is because OFDM techniques have high spectral efficiencies and can reduce the effect of dispersive channels by transferring it to multiple flat channels. The orthogonality property of OFDM is used to scale a high data rate digital signal into multiple lower speed subcarriers. This leads to a reduction in inter symbol interference and the use of simple receiver components. Recently, OFDM techniques have been proposed for optical transmission systems [IV–X] since they are more resilient to channel dispersion when compared to conventional time-division multiplexing techniques[XI]. In addition, they are more spectrally efficient than wavelength division multiplexing (WDM) techniques, since they employ the orthogonality property of subcarriers [VI]. Moreover, OFDM engenders many advantages, such as immunity to chromatic dispersion (CD) and polarization mode dispersion (PMD) in radio-over-fiber transmission systems [XII–XVII]. On the other hand, OFDM techniques suffer from high peak-to-average power ratios and are more sensitive to both carrier frequency offset and phase noise (PN) [II, VIII]. PN on an OFDM
transmission system causes a phase rotation term on each subcarrier. This destroys the orthogonality of subcarriers and results in inter carrier interference [XIX, XX]. Generally, OFDM systems utilize electronic processing in both forward fast Fourier transform (FFT) and inverse FFT modules. Both modules require high-speed digital signal processing, a digital-to-analog converter, and an analog-to-digital converter. The aforementioned processes restrict the OFDM symbol modulation speed. In all-optical OFDM systems, optical FFT (OFFT) is used instead of electrical FFT, and thus, a higher speed can be achieved [XXI]. This is attributed to the optical sampling window, which is sized using electro-absorption modulators (EAMs) and is significantly shorter than its electrical counterpart [XXII]. Additionally, OFFT is more efficient than that of electrical FFT in terms of power consumption due to the use of passive components excluding tuning circuitry and time gating. In conventional optical OFDM systems, both FFT and IFFT are typically performed in the electronic domain, and they, therefore, limit the transmission bit rate. Until now, real-time electronic IFFT and FFT signal processing for optical OFDM signals up to 101.5 Gb/s has been demonstrated [XVL]. This limitation seems to be too far-fetched to reach desirable values for the generation or reception of multi-Terabit per second (Tbit/s) OFDM signals. The all-optical solution that could work beyond the state-of-art electronics speed would, therefore, be of immense interest. In the AO-OFDM systems, the OFDM subcarriers are optically generated and IFFFT/FFT processing is optically implemented by utilizing optical components. Each subcarrier is modulated by using external modulator and it carries a high data information rate as compared with classical OFDM subcarriers. Therefore, large transmission capacity and a higher bit rate can be accomplished by AO-OFDM systems [XIII]. The real-time generation of AO-OFDM signals by real-time optical FFT processing of 10.8 Tbit/s and 26 Tbit/s has been experimentally demonstrated [XXII]. In this research, the all-optical OFDM system using an optical frequency comb source is demonstrated. Additionally, the performance of the proposed system is investigated.

II. Description of AO-OFDM System

The configuration of AO-OFDM system is illustrated in Fig.1. It consists of the following three subsystems:

Transmitter side:

The transmitter subsystem consists of an OFC source, optical de-multiplexer (De-Mux), optical QAM modulators (QAM mod.), and an optical multiplexer (Mux), as displayed in Fig.1. The OFC source part utilizes a frequency modulator (FM) and two Mach-Zehnder modulators (MZMs) driven directly by a sinusoidal RF signal. Comb generation is essential for all-optical OFDM systems because different subcarriers have to be generated from the same laser source to have sufficient coherence and preserve the orthogonality among the OFDM subcarriers. The generated comb lines by an OFC source are split by the optical demultiplexer and simultaneously applied to external optical modulators. These subcarriers are individually modulated using optical QAM modulators. An optical QAM modulation signal is generated from an IQ modulator comprising of two Mach Zehnder modulators (MZMs) with two orthogonal components. The in-phase component of
the intricate envelope modulates the optical carrier within the upper arm, while the quadrature-phase component modulates the 90° stage shifted optical carrier in the lower arm. The QAM encoder is supplied by two independent branches of pseudo-random binary sequence (PRBS) signals. After the optical OFDM subcarriers are modulated, they are then aggregated by an optical multiplexer to form the optical OFDM signal. To preserve the orthogonality of the OFDM signals, the OFDM symbol duration is set to \( T_s = 1/\Delta f_s \), where \( \Delta f_s \) is the comb frequency spacing. That is, no guard interval is used because the symbol duration is equal inverse comb frequency spacing.

**Optical Link:**

The transmission link utilizes \( N_{\text{span}} \) identical spans. Each fiber span consists of a standard single-mode fiber (SMF), a dispersion compensating fiber (DCF), and an optical amplifier (OA), as shown in Fig. 1. A full periodic dispersion map is adapted to compensate for the dispersion by employing a DCF after the SMF (i.e., post-compensation). For compensating the fibers losses, OAs are employed.

**Receiver side:**

The AO-OFDM receiver comprises optical fast Fourier transform (OFFT) circuit, an optical band-pass filter (OBPF), and optical QAM demodulators (demod.), as shown in Fig. 1. The OFFT circuit consists of cascaded Mach-Zehnder interferometers (MZIs), optical de-multiplexers, and electro-absorption modulators (EAMs). The lower arm of each MZI includes optical time delayer and phase shifter. The first MZI time delay is adjusted to \( T_s/2 \), while the time delay of two other subsequent parallel MZIs is set to \( T_s/4 \). The phase shift is set to \( \pi/2 \) rad. Optical de-multiplexers are directly employed to split and filter the subcarriers. After that, the resulting signals were sampled by EAMs. Afterward, the output from each EAM is filtered by the optical band-pass filter and then detected by using optical QAM demodulator.
Fig. 1 Schematic diagram of AO-OFDM system
III. Simulation Results and Analysis

The proposed filter is simulated using VPI transmission Maker® commercial software, the numerical simulation results of investigation performance of the AO-OFDM system are demonstrated. First, explore the process of the generated signal at the transmitter and the detected signal at the receiver. The corresponding optical spectra of the signals were plotted. Then, the influence of the comb power on the performance of the AO-OFDM system was explored by studying the relation between the bit error rate (BER) and the error vector magnitude (EVM) versus the comb power as well as the number of comb lines. Moreover, the constellations and eye diagrams for 4-QAM format were examined with the varying fiber length of the system. The AO-OFDM system performance was investigated using 4-QAM modulation format for both 31 and 51 comb lines. To explore the scenario of the generated and detected the optical OFDM signal in AO-OFDM system, the process of the signal generation at the transmitter side and signal detection at the receiver side are plotted in Figs. 2 and 3, respectively. At the transmitter side, the optical frequency comb source optically provided 31 comb lines with the frequency spacing of 25 GHz, as shown in Fig. 2 (a). After splitting the comb spectrum into single comb lines (called subcarriers) using optical demultiplexer, as shown in Fig.2(b). These separated comb lines (i.e., subcarriers) were modulated independently using optical 4-QAM modulators, as displayed in Fig.2 (c). Each separated comb line was modulated at a symbol rate equal to 25 Gsymbol/s, that corresponds to the frequency spacing of the comb lines. In this point, the total data rate is equal to $2 \times 31 \times 25$ Gsymbol/s = 1.55 Tbit/s. The modulation symbols for each separated comb line were generated by two independent pseudo-random binary sequence (PRBS) signals, each has a length of $(2^{11} - 1)$ bits using a QAM encoder, which generates both the in-phase and quadrature components. Each separated comb line is split by a 3dB coupler and launched into two parallel MZMs. The in-phase component of the intricate envelope modulates the separated comb line within the upper arm, whereas the quadrature-phase component modulates the $90^\circ$ shifted separated comb line in the lower arm, and they are combined by another 3dB coupler. Next, all modulated comb lines (i.e., 4-QAM signals) are recombined by the optical multiplexer, yielding an aggregated AO-OFDM output signal, as depicted in Fig.2 (d). To preserve the orthogonality of the OFDM, the symbol duration of the OFDM is required to be $T_s = 1/\Delta f_s = 40$ ps.
Fig. 2 Optical spectra of obtained signals at the transmitter for 4-QAM AO-OFDM system employed 31 comb lines (a) Comb lines, (b) separated comb line, (c) QAM signal, (d) generated optical OFDM signal

At the receiver side, the received optical OFDM signal is processed using all-optical fast Fourier transform (OFFT) circuit, as shown in Fig.3(a). The scheme of 4-order OFFT is used to perform both serial-to-parallel conversions and FFT in the optical domain using three cascaded Mach–Zehnder interferometers (MZIs) with subsequent time gates (i.e., optical demultiplexers and EAMs), and six couplers. The first MZI time delay was adjusted to $T_s/2 = 20$ ps, while the time delays of each of the two subsequent parallel MZIs was set to $T_s/4 = 10$ ps. After being processed by the OFFT, the resulting signals were sampled by the EAM for the intended comb lines, as displayed in Fig.3(b). Afterward, the output from each EAM was filtered by an optical third-order band-pass filter (OBPF), as depicted in Fig.3(c). Then, detected the filtered QAM signal using QAM demodulator to retrieve the data.
The same scenario of generation and detection optical OFDM signal is used when the AO-OFDM system employed 51 comb lines. Therefore, only the generated AO-
OFDM signal is plotted, as shown in Figure 4. In this case, the total data rate is equal to $2 \times 51 \times 25 \text{ Gsymbol/s} = 2.55 \text{ Tbit/s}$.

![Optical spectrum of the generated optical OFDM signal with 51 comb lines](image)

**Fig. 4** Optical spectrum of the generated optical OFDM signal with 51 comb lines

The comb power affected the performance of the AO-OFDM system. Therefore, the BER and EVM as a function of the comb power at different fiber lengths for different comb lines number are obtained. Figure 3.28 depicts the BER and EVM as a function of the comb power for 4-QAM AO-OFDM system, where the comb power is varied from -15 dBm to 7 dBm. The fiber length is taken in the range from 0 km (i.e., the transmitter is directly connected to the receiver which is called back-to-back (B2B)) to 220 km as well as the comb lines number is 31 and 51. Both BER and EVM results for AO-OFDM system in the absence of optical channel (B2B) are shown in Fig. 5(a) and (b), respectively. B2B measurement served as a reference for the overall system performance. As can be seen that the BER and EVM decrease as the comb power increases. Fig. 5(c) and (d) show the BER and EVM results for AO-OFDM system in presence of optical channel, where the signal is transmitted over transmission distance ranging from 55 km to 220 km. It can be observed that the BER and EVM are initially decreased with rising comb power. However, as the comb power increases beyond 1 dBm, the BER and EVM increase dramatically, at 31 comb lines and fiber length of 55 km. Similarly, when increasing the fiber length to 110 km, the BER and EVM decrease as the comb power increases until the comb power reaches -1 dBm, beyond which the BER and EVM start to increase. By increasing the fiber length to 220 km, the minimum BER and EVM are obtained at the comb power of -3 dB. Similar observations can be made for AO-OFDM system employed 51 comb lines. When the fiber length equals 55 km, the comb power increases beyond -3 dBm, the BER and EVM would increase. By increasing the fiber length to 110 km, the minimum BER and EVM are obtained at the comb power of -5 dBm. In the same manner, by increasing the fiber length to 220 km, the minimum BER and EVM are
achieved at the comb power of -7 dBm. When the comb power increases BER and EVM are increased as displayed in Fig. 5(c) and (d). This is due to the impairment of the fiber nonlinearities at higher powers. Generally, the AO-OFDM system with 31 comb lines has better BER and EVM as compared with the system that uses 51 comb lines.
The results displayed in Fig. 5(c) and (d) are summarized in Table 1. Investigating the results in Fig.5 highlights the following findings:

- The BER and EVM initially decrease as increasing the comb power, since the phase noise due to the integration of ASE noise becomes higher at low powers. While, as the comb power increases, the BER and EVM increase dramatically, since the phase noise due to the interaction of nonlinear effects
such as FWM with ASE noise become dominant at high powers. Therefore, an optimum comb power can be used that gives minimum BER and EVM.

- As the number of comb lines increases, the optimum comb power moves toward lower power region. This is due to the fact that the phase noise increases as the number of comb lines increases.
- With longer transmission distance, the optimum comb power moves toward lower power region. This is due to the impairment of fiber nonlinearities.

Table 1: Minimum BER and EVM at optimum comb power

| N  | Fiber length (km) | Optimum comb power (dBm) | Minimum BER  | Minimum EVM |
|----|------------------|--------------------------|--------------|-------------|
| 31 | 55               | 1                        | 1.57×10-12   | 0.141       |
|    | 110              | -1                       | 3.18×10-12   | 0.143       |
|    | 220              | -3                       | 1.83×10-11   | 0.152       |
| 51 | 55               | -3                       | 6.5×10-12    | 0.145       |
|    | 110              | -5                       | 2×10-10      | 0.164       |
|    | 220              | -7                       | 1.3×10-9     | 0.18        |

For performance measurement of the AO-OFDM system, constellation diagrams and the corresponding eye diagrams are illustrated in Figs. 5 and 6, respectively. The constellation diagram describes the signal that digitally modulated, presenting it as a two-dimensional dispersion diagram. Figs. 5 and 6 display the constellation diagrams and the corresponding eye diagrams of the 4-QAM AO-OFDM signal for 31 and 51 comb lines at transmission distances of 55 km, 110 km (2 spans), 220 km (4 spans), and 440 km (8 spans). These diagrams were obtained for 193.1 THz channel at the output of the 4-QAM receiver. Furthermore, these simulation results are obtained at optimum comb power for each comb lines number at each transmission distance. Where the ideal constellation is plotted by a blue sphere. Fig. 5, it is shown that the AO-OFDM employed 31 comb lines produces clearer constellation diagrams compared to that of the 51 comb lines. In addition, as the transmission distance increases the constellation is squeezed for both comb lines numbers.

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Fig. 6 Received constellation diagrams after transmission over (a) 55 km, (b) 110 km, (c) 220 km, and (d) 440 km. Left-hand side: N=31, Right-hand side: N=51.
It is clear from Fig. 6 that, the eye diagrams for AO-OFDM employed 31 comb lines are clearer than that of the 51comb lines. Moreover, the eye openings slowly close with increasing the transmission distance. From Fig. 6, this degradation of signal due to increasing the noise and the fiber nonlinearities. The difference in timing and amplitude from bit to bit cause the eye-opening to shrink. For Fig. 6, there is an open eye for each case that shows a possible successful reception.

(a)  
(b)  
(c)
The basic aim of this paper is to design and investigate the performance of AO-OFDM system using optical frequency comb by employing different comb lines numbers (e.g., 31 and 51 line), each comb line has been modulated by a quadrature amplitude modulation (4-QAM) format with a symbol rate of 25 Gsymbol/s. Moreover, the influences of the comb power, number of comb lines, and transmission distance on the performance of AO-OFDM system have been quantitatively explored. The total capacity of the system increases as the number of comb lines increases. However, system performance is degraded. Data rates of 1.55 and 2.55 Tbit/s can be achieved at the threshold bit error rate of $\text{BER} = 1 \times 10^{-3}$ over a transmission distance of 3000 and 1500 km using 31 and 51 comb lines, respectively.

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