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Transmission performance of all-optical domain orthogonal frequency division multiplexing signals due to fiber nonlinearities for long-reach PON applications

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ABSTRACT

This study examined the performance of 110 Gb/s all-optical domain orthogonal frequency division multiplexing (AO-OFDM) signal transmission systems using optical multi-carrier generation and optical 2-subcarrier modulation under the effects of chromatic dispersion and fiber nonlinearity. The numerical simulation results showed that the performance degradation of AO-OFDM signals lies in the inter-carrier interference between the subcarrier signals generated from the fiber nonlinearities. The numerical simulation showed that the calculated BER of the AO-OFDM channels has some power penalties at 10^{-9} BER for the fiber chromatic dispersion effect. The calculated receiver sensitivity at 10^{-9} BER showed additional degradation at the central subcarrier channel by applying a fiber launching power of 12 dBm after transmission over a 100 km standard single-mode fiber (SMF) link. The simulation results are expected to be useful for multi-service systems employing AO-OFDM technology in the future long-reach passive optical network (PON) applications.

1. Introduction

Passive optical network (PON) technology is considered one of the most promising solutions for providing high bandwidth to end-users in a cost-effective manner [1,2]. Among the many optical access network architectures proposed, PON is most favorable for network operators in terms of maintenance and operation. Although several techniques have been considered for the next-generation PON (NG-PON) technologies in future high-capacity optical access networks, OFDM-PON has also been envisioned as a prominent modulation and multiplexing technique with its superior tolerance to chromatic dispersion and polarization mode dispersion (PMD) of the optical fiber channel [3–5]. The maximum achievable data-rate per user can be increased up to 100 Gb/s using optical OFDM technologies.

Coherent optical OFDM (CO-OFDM) have been actively investigated for applications to ultra-long haul transmission systems [6,7]. An AO-OFDM technique was proposed because the number of the signal subcarriers can be reduced in AO-OFDM systems compared to conventional optical OFDM techniques. This technique requires no guard-interval between the OFDM symbols [8,9].

Recently, there has been increasing interest in long-reach PON by network operators to satisfy the increasing demands for higher capacity and quality of service (QoS), and solve the bottleneck problem in the electronic interface within optical network systems [10,11]. The transmission distance of long-reach PON can be longer than 80 km and it can be integrated with existing optical networks, such as optical metro core networks and conventional PON systems, resulting in a significant decrease in the electronic interfaces and an increase in the cost-effectiveness of the system. AO-OFDM technology can also be used in long-reach PON systems to support a data rate >100 Gb/s per user in an access network with a transmission distance up to 100 km.

Several studies have examined AO-OFDM signal transmissions [12–14], including the experimental demonstration of 110 Gb/s AO-OFDM signals over 80 km SMF link [12], and 35 Gb/s AO-OFDM transmission over an 84 km SSMF link using a photonic integrated optical DFT device [14]. These previous studies highlighted the feasibility of AO-OFDM signal transmission for a total data rate >30 Gb/s with the transmission performance against the fiber dispersion effect.

Although many investigations about the effect of fiber nonlinearity in the electro-optically modulated optical OFDM systems exist [15–17], a detailed analysis of the transmission performance of AO-OFDM systems with the fiber nonlinear effects was not performed.

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This study examined the performance of 110 Gb/s AO-OFDM signal transmission systems under the effect of fiber nonlinearity and chromatic dispersion based on numerical simulations. The optical 2-subcarrier modulation method was used to implement a 22-channel AO-OFDM transmitter and a cascaded Mach–Zehnder delay interferometer (MZDI) structure for the separation of each AO-OFDM channel. The bit-error-rate (BER) and receiver sensitivities at 10^{-9} BER of the different AO-OFDM channels were analyzed after transmission over the SMF link.

This paper is organized as follows: Section 2 describes the theoretical background regarding the configuration of 110 Gb/s AO-OFDM transmitter and receiver. Section 3 explains the configuration of a 22-channel AO-OFDM signal transmission link and the parameters used in the simulations. Section 4 presents the results of the numerical simulations. First, the optical power spectra of various signals with different data modulation formats are compared. Second, BER performance of AO-OFDM signals is reported. Third, the receiver sensitivities at 10^{-9} BER versus fiber launching power of AO-OFDM signals are calculated. Finally, the conclusions are provided in Section 5.

2. Theoretical background

Generally, high-speed FFT operations are processed in the electrical domain in the conventional CO-OFDM systems. On the other hand, previous studies reported the feasibility of the optical discrete-Fourier transform (DFT) operation based on the analogy between the electrical domain DFT operation and the optically time and phase-shifted structure. The optical DFT operations can be implemented in an all-optical manner using optical passive devices, such as optical delay lines and optical phase shifters [8]. AO-OFDM systems can reduce the load of electronics, such as high-speed inverse-FFT (IFFT) and FFT block, by employing all-optical domain DFT operation, compared to conventional optical OFDM systems. Therefore, the power consumption of the electronics can be reduced and the signal processing speed can be increased. Moreover, the AO-OFDM system can be used in signal processing technologies and optical devices for existing 10 Gb/s optical systems to construct a system data rate >100 Gb/s because it employs multiple tributaries of signals with a data rate of 10 Gb/s or lower.

2.1. Configuration of 110 Gb/s AO-OFDM transmitter

Several techniques to construct AO-OFDM transmitting signals have been proposed in the previous studies to satisfy the orthogonal condition in the optical frequency domain [12,14]. We adopted the optical 2-subcarrier signal modulation method to generate an elementary component for the entire multi-channel AO-OFDM signal [12].

$$S_I(t) = (D_1(t) + D_2(t))\cos\left(2\pi \cdot \frac{\Delta f}{2} t\right), \tag{1}$$

$$S_Q(t) = (D_1(t) + D_2(t))\sin\left(2\pi \cdot \frac{\Delta f}{2} t\right), \tag{2}$$

$$S_{\text{out}}(t) = D_1(t)\cos\left(2\pi\left(f_c + \frac{\Delta f}{2}\right)t\right) + D_2(t) \times \cos\left(2\pi\left(f_c - \frac{\Delta f}{2}\right)t\right), \tag{3}$$

Eqs. (1) and (2) describe the input signals into two different I/Q arm Mach–Zehnder modulators (MZM), and the corresponding optical output signals, $S_{\text{out}}(t)$ from the optical 2-subcarrier modulator can be defined as Eq. (3), where Δf is the optical frequency spacing between the two signal subcarriers [12]. The optical spectra of $D_1(t)$ and $D_2(t)$ satisfy the orthogonal condition in the optical frequency domain, $\Delta f = m \cdot \frac{1}{T}$, where T is a bit duration. $D_1(t)$ and $D_2(t)$ can be separated by using the cascaded MZDI structure in the receiver.

To construct multi-channel AO-OFDM signals, the optical multi-carrier generation method was employed using only one lasing source, such as distributed-feedback laser diode (DFB-LD). One of the main advantages of using an optical multi-carrier generation method is the lower implementation complexity of the optical transmitter due to the use of a single optical source, whereas an array of the multiple laser diodes is used in the case of WDM transmission. Several methods for generating the optical multi-carrier signal, such as a cascaded intensity modulator (IM)–phase modulator (PM) structure and an IM–IM structure, have been proposed [18,19]. Unlike the transmitter configuration reported in Ref. [12], the present study applied the optical comb generation method [20] as the optical multi-carrier generation to provide optical source wavelengths to multiple optical 2-subcarrier modulators.

$D_2(t)$ is composed of a half-delayed version of $D_1(t)$ in the simulations in order to modulate different PRBS data on each optical signal carrier. In general, stability is very important for the optical multi-carrier signal generation. A 10 GHz clock signal is modulated by the optical phase modulator and switching voltage (V_π) of the PM and the peak-to-peak voltage of the time-domain clock signal was optimized to generate an optical multi-carrier signal with less peak-to-peak power deviation. This study achieved a peak-to-peak deviation of less than 3.4 dB for all 10 GHz-spaced 11 optical multi-carriers with a center wavelength of 1550 nm in the numerical simulations. With an enhanced optimization of the peak power of generated optical carriers, we can increase the number of channel to transmit higher capacity signals. The entire AO-OFDM signal can be implemented by electro-optically modulating each optical carrier using the 2-subcarrier modulation method. In order to consider the implementation of upstream connection, the use of MZMs for the I-/Q-arm signal modulation can be substituted with low-cost EAMs for the cost effectiveness.

2.2. Configuration of 110 Gb/s AO-OFDM receiver

An optical DFT operation is required to separate multiple AO-OFDM channels into individual subcarrier signals in an all-optical manner. The optical DFT operation can be implemented using several methods by a combination of passive optical devices, such as optical phase shifters and delay lines [8]. One of the AO-OFDM signal separation methods is a cascaded MZDI structure [12]. This method can separate the AO-OFDM signal carriers at different optical frequencies by changing the frequency response of MZDI. An adjustment of the delay parameter of MZDI and the phase shift can alter the central frequency of the MZDI response into the target AO-OFDM signal subcarrier [21]. After the cascaded MZDI filtering process, the signal was finally passed through an optical band-pass filter (OBPF), whose bandwidth is equal to the desired signal bandwidth (=15 GHz including two overlapped signal subcarriers in our cases) to eliminate the un-wanted signal component in the optical frequency domain. Therefore, the signal demodulation and BER calculation of the two-level optical signal can be followed after this process. We used a PIN receiver for the photo-detection with the quantum efficiency of 1 and the receiver circuit noise of 17 pA/Hz$^{0.5}$.

3. Simulation setup for 110 Gb/s AO-OFDM transmission system

Fig. 1 shows the block diagram of a 22 channel 110 Gb/s AO-OFDM transmission system used in the simulation. The wavelength of the source laser diode was set to 1550 nm and the optical multi-carrier generator, including phase modulation of the 10 GHz clock signal, provided 11 optical multi-carrier signals