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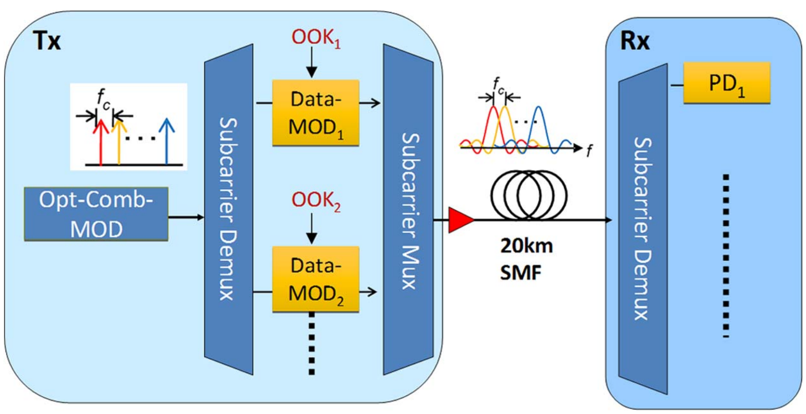

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Cost-Effective Direct-Detection All-Optical OOK-OFDM System With Analysis of Modulator Bandwidth and Driving Power

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Abstract: Optical orthogonal frequency-division multiplexing (OFDM) with advanced modulation format [e.g., quadrature amplitude modulation (QAM) and quadrature phase-shift keying (QPSK)] provides many transmission advantages. As the OFDM data rate is limited by the electronic digital-to-analog (DAC) and analog-to-digital (ADC) integrated circuits, an all-optical technique (i.e., all-optical OFDM) is used to construct an OFDM symbol; hence, it can provide a significant improvement in transmission capacity. In this work, we propose and demonstrate a cost-effective 275-Gb/s direct-detection all-optical OFDM system for access or data center networks. As all wavelength channels (11 wavelengths in the experiment) are produced by one laser source, only the temperature control of one master laser is enough. In addition, each wavelength channel in the all-optical OFDM signal is encoded using on–off keying (OOK) modulation format; the traditional generation and detection circuits used in the transmitter (Tx) and receiver (Rx) of the present passive optical network can still be used. We also numerically analyze the requirements of the opt-comb-MOD (modulator used to generate the optical comb source) and the data-MOD (modulator used to generate the OOK data) in the system.

Index Terms: Optical communications, wavelength-division-multiplex passive optical network (WDM-PON), fiber optic communications.

1. Introduction

We have witnessed a significant increase in bandwidth demand in access networks and data center networks for the past few years. Increasing network capacity and reach are considered as important features for the future networks. Wavelength division multiplexing (WDM) is a simple way to increase the network capacity by using different wavelength channels to carry different data [1]–[3]. However, in order to fit the increasing number of WDM channels into a bandwidth limited gain spectrum of an optical amplifier (typical erbium-doped fiber amplifier (EDFA) and semiconductor optical amplifier (SOA) have fixed and limited gain bandwidth of ~30 nm), the wavelength separation should be reduced significantly. Precise wavelength control of each WDM channel is needed to avoid channel overlap between different WDM channels. This highly increase the wavelength management cost (for temperature and wavelength control of a large number of WDM wavelength channels), especially in the cost-sensitive access and data center networks.

Optical orthogonal frequency division multiplexing (OFDM) with advanced modulation format [e.g., quadrature amplitude modulation (QAM) and quadrature phase shift keying (QPSK)] have been proposed and demonstrated to provide high spectral efficiency, high chromatic dispersion tolerance and high bandwidth allocation flexibility for future passive optical networks (PON) [4]–[7]. Besides, coherent detection (CD)-OFDM can provide a higher transmission performance; however complicated and costly receiver (Rx) is required. Hence, direct-detection (DD) could be more suitable for the cost-sensitive access and data center networks [8], [9]. As the optical OFDM data rate is limited by the electronic digital-to-analog (DAC) and analog-to-digital (ADC) integrated circuits (IC) used to generate and decode the OFDM signal, all-optical technique [10] can be used to remove the bottle-neck of the electronic DAC/ADC. In the all-optical OFDM, optical technique is used to construct an OFDM symbol instead of using the electrical one; hence, without speed-limitation by the electronic IC, all-optical OFDM thus can provide significant improvement in transmission capacity.

In this work, we propose and demonstrate a cost-effective DD OFDM system for access (20 km standard single-mode-fiber (SMF) transmission without dispersion compensation) or data center networks. As all wavelength channels (11 wavelengths generated in the experiment) in the all-optical OFDM signal are produced by one laser source, there is no need of wavelength and temperature control of different individual wavelength channels. Only the temperature control of one master laser is enough. In addition, each wavelength channel in the all-optical OFDM signal is encoded using on-off keying (OOK) modulation format, the traditional generation and detection circuits used in the transmitter (Tx) and Rx of present PON can still be used. A 275 Gbit/s DD OFDM system is demonstrated since only a moderated driver of 22 dBm is used to produce the optical comb. Hence, we also numerically analyze the requirements of the opt-comb-MOD (modulator used to generate the optical comb source) and the data-MOD (modulator used to generate the OOK data) in the system. We study the driving power requirement of the opt-comb-MOD to produce different optical comb bandwidths. Besides, we also study the bandwidth requirement of the data-MOD. It is generally expected that 25 GHz bandwidth data-MOD is suitable for 25 Gbit/s data transmission. However, in the all-optical OFDM system, we discover that the broader bandwidth is not necessarily beneficial. The results show that using a little narrower bandwidth data-MOD has a better performance. This cannot only improve the performance of the transmission, but also reduce the cost of the system (since an array of lower bandwidth modulators is needed).

2. Proposed Cost-Effective DD All-Optical OOK-OFDM

Fig. 1 shows the proposed architecture of the cost-effective DD all-optical OOK-OFDM system. At the Tx side, an optical comb source is generated by the opt-comb-MOD with frequency separation of f_c. Then the comb lines are wavelength demultiplexed, and then encoded by OOK data via an array of data-MODs. By using proper delay among different subcarriers, they are then multiplexed to produce the all-optical OFDM signal. At the Rx side, only a wavelength demultiplexer is needed to demultiplex different subcarrier channels, which is then detected by photodiodes (PDs).

In a traditional WDM system, if the channel separation is not large enough, crosstalk produced by adjacent channels will highly degrade the target channel. Fig. 2 shows the schematic optical spectra and simulated eye-diagrams (using VPI Transmission Maker V7.5) for illustrating the operation principle of the proposed all-optical OFDM system. Considering the a wavelength channel at f_0 [see Fig. 2(a)] after passing through an optical filter which is represented by the dotted line, crosstalk from the high frequency components of the two adjacent channels will also located inside the pass-band of the optical filter, as shown in Fig. 2(b). After combining the

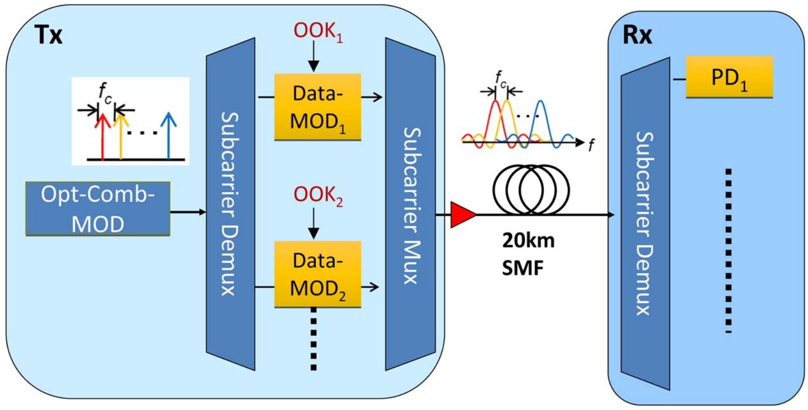

Fig. 1. Architectures of proposed cost-effective DD all-optical OOK-OFDM system.

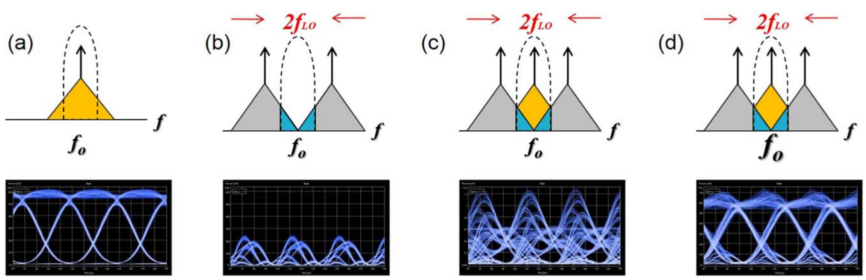

Fig. 2. Schematic optical spectra and simulated eye-diagrams of the AO-OFDM-SC.

signals from all the channels, the eye diagram will be corrupted due to the transient components of the neighbor signals in time-domain, as shown in Fig. 2(c). In order to improve the eye-opening, proper time-delay of neighbor channels are adjusted so that these transients align with the eye crossing-point of the target channel, and therefore, the clear eye-opening can be achieved, as shown in Fig. 2(d). This can be achieved if all the channels are phase-locked.

3. Proof-of-Concept Experimental Demonstration and Results

Fig. 3 shows the proof-of-concept experiment setup of the proposed DD all-optical OFDM system. A distributed feedback laser diode (DFB-LD) at wavelength of 1548.3 nm was launched into the phase modulator (PM) with modulation bandwidth of 35 GHz, which acted as the opt-comb-MOD. It was driven by a 25 GHz electrical clock signal to generate an optical comb. In this system, 11 optical tones (optical carriers) with high optical signal-to-noise (OSNR) were chosen to carry the data. The odd and even subcarriers were separated by a 25-GHz/50-GHz optical interleaver (IL) and then respectively modulated by two different (decorrelated) 25 Gbit/s, pseudorandom binary sequence (PRBS) $2^{31}-1$ OOK signals via two Mach–Zehnder modulators (MZMs) with modulation bandwidth of 35 GHz. Then the odd and even subcarriers were combined by using a passive optical coupler with proper delay between them. It was adjusted by a variable optical delay-line (DL). Hence, a 275 Gbit/s (25 Gbit/s $\times$ 11) all-optical OFDM signal was achieved. Then the all-optical OFDM signal was launched into a 20-km SMF for transmission. At the Rx, the all-optical OFDM signal passed through an optical band-pass filter with bandwidth of $\sim$25 GHz. One of the subcarriers was filtered out and received by a PD for performance analysis.

Fig. 4 shows the optical spectra measured by an optical spectrum analyzer (resolution of 0.01 nm) at different locations of Fig. 3. The comb source produced by the PM driven by a 25 GHz clock signal is shown as Fig. 4(a). The frequency spacing of optical comb is 25 GHz. After the IL, the odd and even optical comb were separated [shown in Fig. 4(b) and (c)] and then

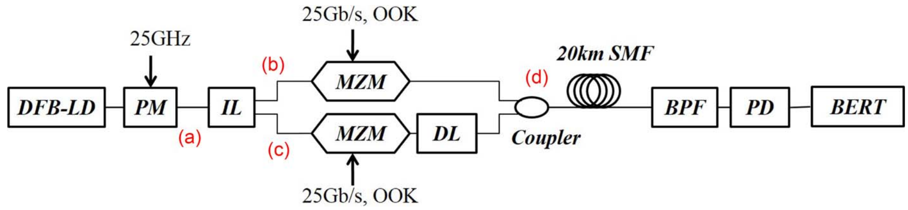

Fig. 3. Experiment setup of all-optical OFDM system. PM: Phase modulator. IL: Interleaver. MZM: Mach–Zehnder modulator. DL: Delay line. SMF: Single-mode fiber. BPF: Band-pass filter. PD: photo-diode.

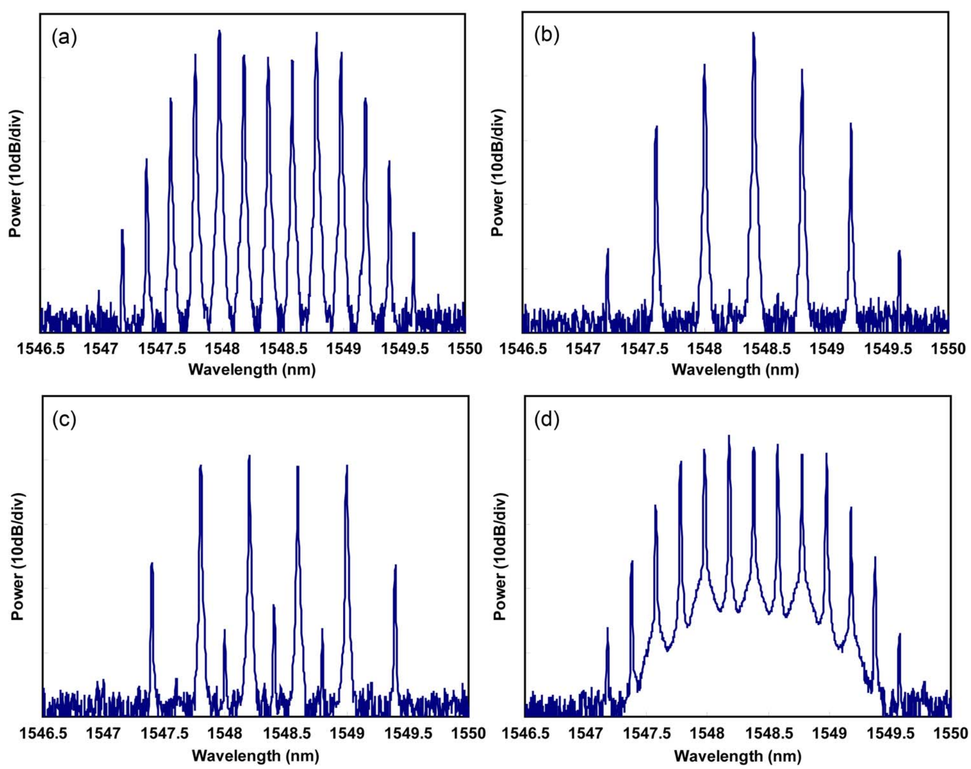

Fig. 4. Measured optical spectra at different locations of the all-optical OFDM system.

modulated by 25 Gbit/s data, respectively. Finally, Fig. 4(d) shows the spectrum of the combined signals measured after the optical coupler. By comparing Fig. 4(a) and (d), we can observe the spectral width of each subcarrier becomes wider due to successful OOK data encoding. The selected 11 subcarriers with higher OSNR can produce the 275 Gbit/s all-optical OFDM signal.

Fig. 5 shows the bit-error-rate (BER) measurement of an arbitrary subcarrier channel from the all-optical OFDM signal, which was filtered out by the optical band-pass filter. We can observe that although there is a large spectral overlap among the subcarriers (as described in Section 2), by adjusting the proper time-delay, the all-optical OFDM signal can be de-multiplexed (filtered out) and satisfy the forward error correction (FEC) requirement of 3.8×10^{-3} (dotted line) after 20 km of SMF transmission without dispersion compensation. The 25 Gbit/s eye-diagrams from experiment and simulation are also included in the insets.

4. Analysis of Modulator Requirements

In the proof-of-concept demonstration mentioned above, only a 275 Gbit/s (25 Gbit/s $\times$ 11) all-optical OFDM signal was achieved. This is because only typical moderate power modulator

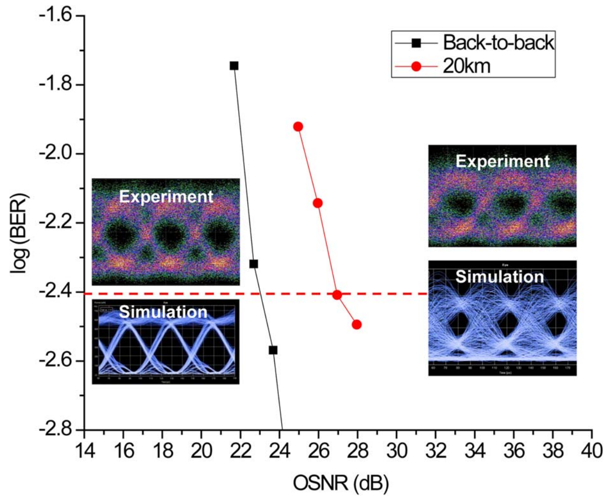

Fig. 5. Experimental BER measurements. (Insets) Eye-diagrams from experiment and simulation.

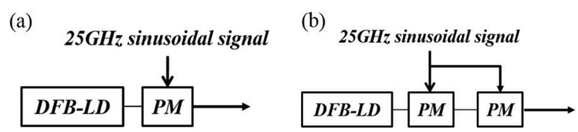

Fig. 6. Simulation Tx setup to produce different bandwidth of optical comb using (a) a single PM and (b) a cascade of two PMs.

driver was used with output electrical power of ~22 dBm to drive the opt-comb-MOD. Hence the number of generated Bessel comb lines with high enough OSNR ($>$ 20 dB) was only 11, occupying a bandwidth of ~275 GHz. We numerically analyzed the driving power requirement for the opt-comb-MOD using VPI Transmission Maker V7.5. The Tx setups of using a single PM and using cascaded PMs are shown in Fig. 6(a) and (b), respectively. The 25 GHz driving power to each PM was the same. In each case, the optical continuous wave (CW) signal produced by the DFB-LD was launched into the PM(s). The OSNR of the generated optical combs were analyzer at the output in frequency domain.

Fig. 7(a) shows the simulation results of the electrical driving power required to produce different optical Bessel comb bandwidth. As shown in the results, when the driving power is 22 dBm, the optical comb bandwidth is about 275 GHz. When 400 Gbit/s all-optical OOK-OFDM data rate is needed, electrical driving power of 28 dBm is needed to produce 400 GHz optical comb bandwidth. This increase the deployment cost since higher power modulator driver is needed, and the modulator driver output power is not increasing linearly with the cost. Instead of increasing the electrical driving power, cascading two PMs for the opt-comb-MOD can be considered, in which the two PMs are electrical driven by two modulator drivers. Fig. 7(b) shows the simulation results of using a cascade of two PMs. We can observe that only two 22 dBm modulator drivers are needed to drive the two PMs respectively to generate an optical comb bandwidth of 400 GHz. However, this requires an additional PM and moderated power driver.

Then, we analyzed the requirements of the data-MOD. It is generally expected that 25 GHz bandwidth data-MOD is suitable for 25 Gbit/s data transmission. However, in the all-optical OFDM system, we discover that the broader bandwidth is not necessarily beneficial. If the bandwidth of the data-MOD decreases, the high-frequency components will be attenuated. As a result, the overlap frequency components by the adjacent channel will reduce. When the bandwidth of the data-MOD reduces to certain level, the crosstalk will be weakened a lot. However, reducing the data-MOD bandwidth will degrade the signal performance by introducing

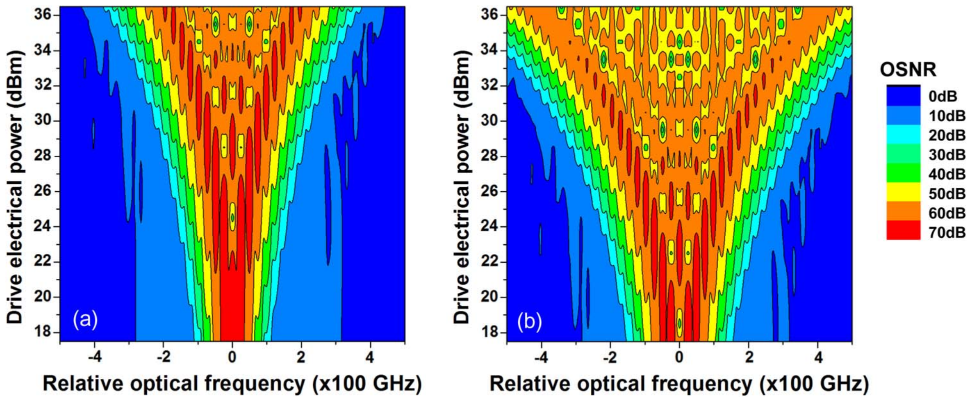

Fig. 7. Simulation results of the electrical driving power required to produce different optical Bessel comb bandwidth using (a) a single PM and (b) a cascade of two PMs.

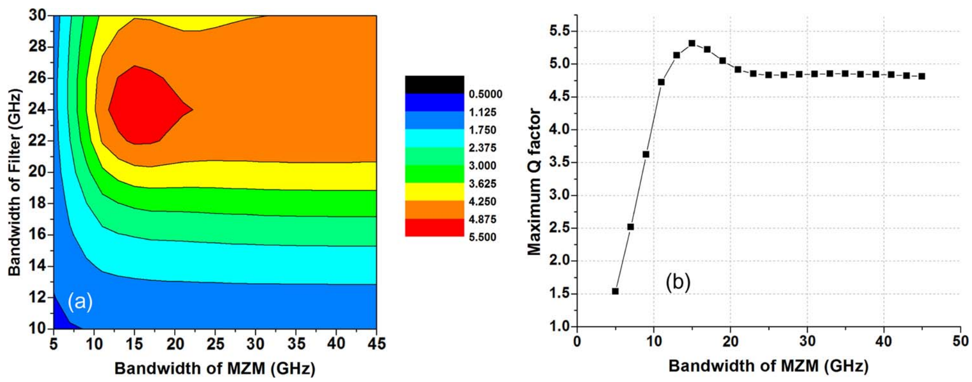

Fig. 8. Simulated Q values (a) of all-optical OOK-OFDM system using different bandwidths data-MOD and different bandwidths of optical filter used to demultiplex one channel, (b) of data-MOD bandwidth at fixed optical filter bandwidth of 24 GHz.

inter-symbol interference (ISI). Fig. 8(a) shows the simulation Q values of the all-optical OOK-OFDM system using different bandwidths data-MOD (1st order Bessel shaped) and different bandwidths of optical filter (1st order Gaussian shaped) used to demultiplex one channel from the all-optical OOK-OFDM signal. By choosing a fixed optical filter bandwidth of 24 GHz, we can observe that the optimum condition of the data-MOD bandwidth is not at 25 GHz or 40 GHz, as shown in Fig. 8(b). Instead, 15 GHz bandwidth data-MOD is suitable for the all-optical OOK-OFDM system, in which each optical carrier was modulated with 25 Gbit/s data. If the data-MOD bandwidth is below 15 GHz, the signal of will be significantly degraded due to ISI. When the data-MOD bandwidth is larger than 15 GHz, the interference from the adjacent channels will become serious causing the Q factor to decrease. When the data-MOD bandwidth is larger than 25 GHz, which is sufficient for the 25 Gbit/s modulation; the interference from adjacent channels will be almost the same as the data-MOD bandwidth increases. Hence, the Q factor becomes stable. The results show that using a little narrower bandwidth data-MOD has a better performance.

5. Conclusion

As the optical OFDM data rate was limited by the electronic DAC/ADC, all-optical technique (i.e., all-optical OFDM) was used to construct an OFDM symbol instead of using the electrical one; hence, without speed-limitation by the electronic IC, all-optical OFDM thus can provide significant improvement in transmission capacity. In this work, we proposed and demonstrated a cost-effective 275 Gbit/s DD all-optical OFDM system for access or data center networks. As all wavelength channels (11 wavelengths in the experiment) were produced by one laser source, only the temperature control of one master laser is enough. In the experiment, 20 km SMF transmission was demonstrated; much higher transmission distance can be achieved with proper dispersion compensation [11]. The total data rate of the proposed system was proportional to the number of optical subcarriers (optical comb) that can be generated, and the number of optical subcarriers produced by the PM depended on the driving power. We also numerically analyzed the requirements of the opt-comb-MOD (modulator used to generate the optical comb source) and the data-MOD (modulator used to generate the OOK data). From the results, when 400 Gbit/s all-optical OOK-OFDM data rate was needed, electrical driving power of 28 dBm was needed to produce 400 GHz optical comb bandwidth; or using two 22 dBm modulator drivers to drive the two PMs respectively. Besides, in the all-optical OFDM system, we discovered that the broader bandwidth data-MOD is not necessarily beneficial. By choosing a fixed optical filter bandwidth of 24 GHz, form the results, a 15 GHz bandwidth data-MOD is suitable for the all-optical OOK-OFDM system, in which each optical carrier was modulated by 25 Gbit/s data. The results showed that using a little narrower bandwidth data-MOD had a better performance.

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