Experimental Demonstrations of 20 Gbit/s Direct-Detection Optical OFDM and 12 Gbit/s with a colorless transmitter

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Abstract: We show experimentally that optical orthogonal frequency division multiplexing using a simple direct-detection receiver can post-compensate for dispersion in 320km of SMF28e fiber at 20 Gbit/s. We also demonstrate a colorless transmitter at 12 Gbit/s.

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1. Introduction

We present experimental results for a new, improved form of optical OFDM [1, 2]. Data was transmitted at 12 Gbit/s over 400 km of standard single mode fiber with no optical dispersion compensation in a system with a colorless transmitter and a direct detection receiver. Standard off-the-shelf, commercial grade, electrical and optical components were used. The high frequency roll-off of the analog components and the chromatic dispersion of the fiber were equalized digitally in the OFDM receiver. This adapts automatically to any changes in channel response. Unlike precompensation techniques [3], no return path is required. The data rates and distances achieved are not inherent limitations of the optical OFDM technique but are limitations of the available equipment. The data rate was limited by the speed of the commercial arbitrary waveform generator (AWG) and the distance was limited by the number of optical amplifiers available. Transmission at 20 Gbit/s over 320 km was also demonstrated. This required an optical filter in the transmitter because the AWG has only a single output at the higher sample rate required.

The new system design is a refinement of our earlier optical OFDM techniques [1, 2]. Optical single sideband transmission ensures that the combination of chromatic dispersion and direct detection does not cause deep spectral nulls. By using the linear-in-field region of the optical modulator and by the careful choice of OFDM subcarrier frequencies, we ensure that no unwanted signal×signal components fall on the used subcarrier frequencies. As a result, the received demodulated signal is virtually free of intermodulation products and the system performance is limited mainly by optical amplifier noise and the frequency response of the AWG.

2. System Design

Figure 1 shows the system design. The OFDM signals are calculated offline in MATLAB and downloaded to a Tektronix AWG7102 which has two independent 10 GS/s digital to analog converters (DACs).

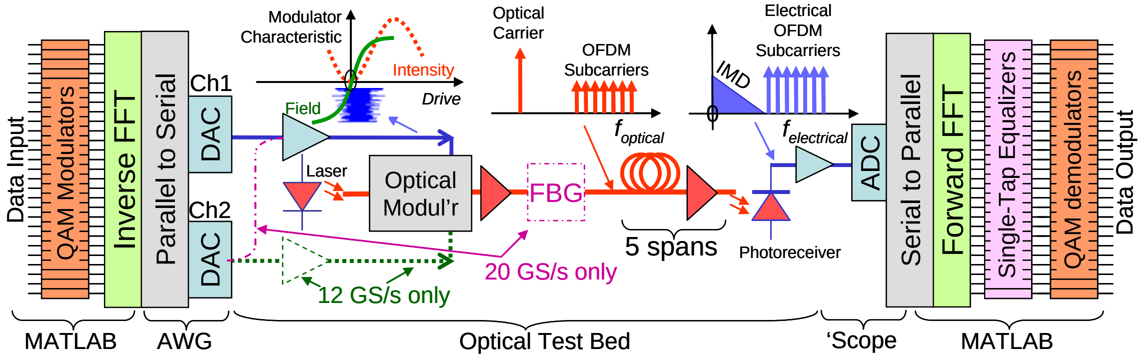


Fig. 1: Experimental direct detection OFDM systems.

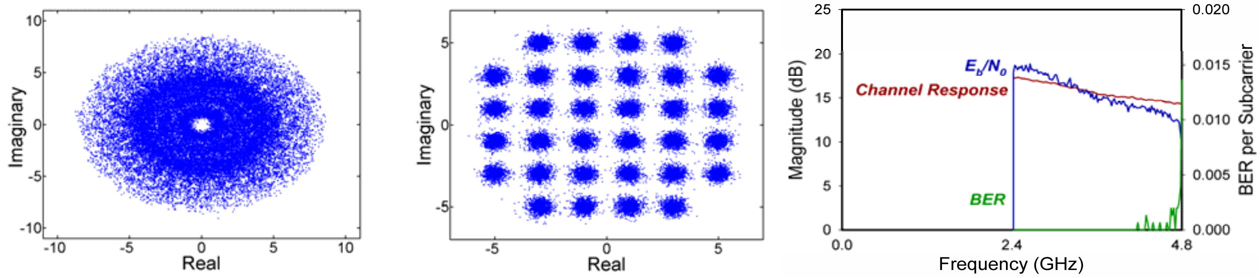
For the 12 Gbit/s colorless implementation, the AWG generates the OFDM signal and its Hilbert transform. These are amplified by Marki A-0200 microwave amplifiers to provide I and Q drives for a Sumitomo Single-Sideband (complex-IQ) optical modulator. In this way, an Optical Single Sideband signal (OSSB) is generated without using an optical filter. The optical input to the modulator is a Photonics tunable laser and the modulator output is amplified and driven through five 80-km spans of Corning SMF-28e fiber with a Lightwaves 2020 MOAPF25 optical amplifier after each span. The system was operated below the nonlinear limit of 0 dBm. A Fiber

Bragg Grating (FBG) in reflective mode is used as an ASE filter (50 GHz FWHM) and the receiver is a Discovery Semiconductors DSCR404. The data is captured using an Agilent 81004A DSO and MATLAB is used to decode and equalize the signal. No sneak wires are used to synchronize the sampling rates of the AWG or the DSO. For the 20 Gbit/s implementation, the AWG is used in *single channel*, *interleaved* and *zeroed* modes to enable a 20 GS/s sample rate. The single channel drives a Fujitsu chirp-free MZI modulator. A second FBG is used to notch out one optical sideband after the modulator. Because of the lower optical power a 30-km fiber span followed by three 80-km spans and one 50-km span are used. For both implementations, the modulators are biased just above their intensity nulls to: (a) provide the optimum carrier to sideband power ratio (1:1) for the best noise performance and (b) to drive the modulators predominantly within the linear field region. In the linear field region, the modulated optical field is proportional to the baseband electrical voltage, so each OFDM subcarrier translates to a single optical frequency. When this signal is downconverted at the receiver photodiode, all of the difference products fall exactly on the difference frequencies of the original electrical OFDM signal. As in [1], subcarriers in the lower half of the frequency range are not used for data transmission (see inset Fig.1). All of the difference products of the used subcarriers fall on these unused frequencies. The used subcarriers are virtually free of intermodulation products.

3. Results at 12 Gbit/s using a colorless transmitter

As both channels of the AWG were required for this experiment, the maximum sample rate was limited to 10 GS/s (5 GHz Nyquist bandwidth). However, a side-mode of the laser caused a noise peak at 4.8 GHz; thus to demonstrate the potential of the system, 32 QAM was chosen for a 12 Gbit/s data rate. A high-QAM system illustrates the low levels of IMD that we can obtain by using a modulator biased linearly in optical field *vs.* drive voltage.

Three hundred random symbols (184,500 bits) were received at a Bit Error Ratio (BER) of 3.03e-4 after a distance of 400 km. The correction of phase distortion caused by OFDM frame timing offsets and chromatic dispersion can be seen in the comparison of the unequalized and equalized constellations of Figs. 2(a) and 2(b). Figure 2(c) shows the system's frequency response drooping at high frequencies causing a reduction in signal to noise ratio, which causes an increased BER for the higher subcarriers.



(a) Unequalized constellation (b) Equalized Constellation (c) Channel response, E_b/N_0 and BER

Fig. 2. Experimental results for the 12 Gbit/s colorless SSB optical OFDM system.

Figure 3 shows the received electrical spectra with both inputs to the complex-IQ modulator driven (left), giving optical single-sideband (OSSB) transmission, and with one disabled (right), giving double-sideband (DSB) transmission. For DSB, a dispersion null can be seen at 3.6 GHz instead of 3 GHz indicating residual chirp in the modulator. The frequency band above 5 GHz is an image due to the AWG's Nyquist limit of 5 GHz.

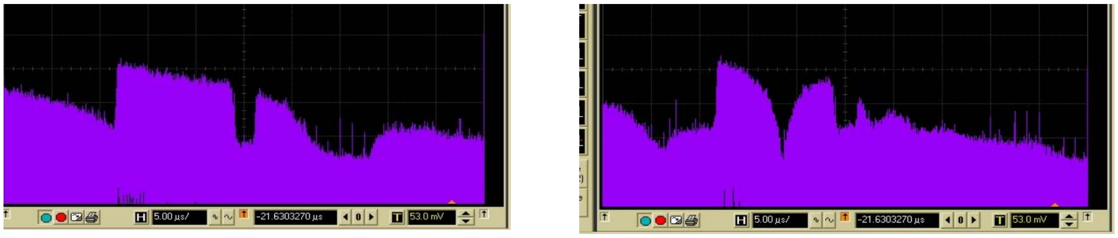
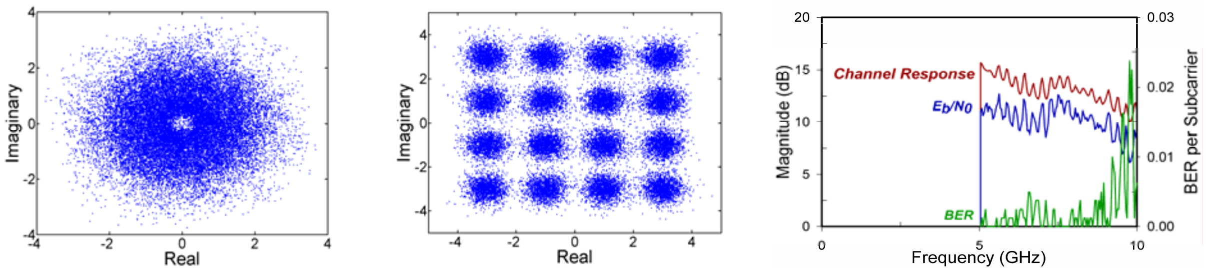


Fig. 3: Spectra for OSSB (left) and DSB (right) transmission. (10 dB/division vertical: 1 GHz/division horizontal)

4. Results for 20 Gbit/s using an optical filter at the transmitter

For 20 Gbit/s transmission, the AWG's DACs were set to give return-to-zero signals, which were interleaved to give a 20-GS/s sample rate and a Nyquist bandwidth of 10 GHz. The signal was then fed to a chirp-free MZI modulator, followed by a Fiber Bragg Grating (FBG) in transmission mode. Because of increased noise from the AWG, 16QAM was used instead of 32QAM. Figs. 4(a) and 4(b) show the constellations before and after equalization. The BER after 320 km was 2.5e-3. Figure 4(c) shows the signal to noise ratio (E_b/N_0) the relative channel response and the BER *vs*. frequency. Dips in the response cause dips in E_b/N_0 and peaks in the BER. A direct connection between the AWG and the DSO showed that the "return to zero" mode is the cause of these frequency response ripples. Because of the frequency response of the AWG, a relatively high OSNR was required in both experiments (22dB and 26dB). A smaller constellation or tighter optical ASE filter would also have reduced the required OSNR.



(a) Unequalized constellation

(b) Equalized Constellation

(c) Channel response, E_b/N_0 and BER

Fig. 4. Experimental results for the 20 Gbit/s OSSB optical OFDM system.

Figure 5 shows the electrical spectra with and without the FBG notch filter. This confirms that OSSB removes the nulls in the baseband response that are caused by the fiber's dispersion.

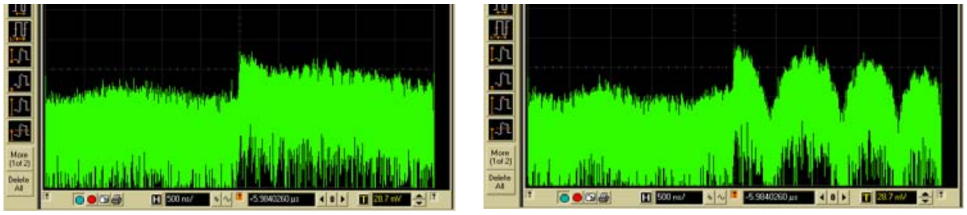


Fig.5: Spectra for OSSB (left) and DSB (right) transmission. (10 dB/divison vertical: 1 GHz/division horizontal)

5. Conclusions

We have presented the first experimental demonstration of direct detection optical OFDM with 12 Gbit/s using a colorless transmitter and 20 Gbit/s using an optical filter at the transmitter. Direct detection has many advantages over coherent OFDM [4] as standard off-the-shelf components can be used to build high performance systems. In contrast, because of the well known sensitivity of OFDM to frequency offset and phase noise [5,6], coherent OFDM systems require very narrow linewidth lasers at both the transmitter and receiver. In our new system, the signal is recovered by mixing between the OFDM optical sideband and the optical carrier, so distortion from phase noise and frequency offset is completely eliminated. This also means that, unlike coherent systems, the overall channel response changes only very slowly with time, so only infrequent pilot symbols are required to train the equalizer and the overhead is very low. The system performance scales with the speed of the DACs allowing higher data rates and/or increased receiver sensitivity.

Acknowledgements

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