Optical OFDM for High-Speed Transmission

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Abstract
Optical orthogonal frequency division multiplexing for high-speed, long-haul optical transmission systems is reviewed. Some important aspects of the systems are discussed and demonstrations of high-speed transmission up to 122 Gbit/s are presented.

1. Introduction

Orthogonal frequency division multiplexing (OFDM) is an attractive modulation format that recently received a lot of attention in the fiber-optic community [1, 3-9]. The main advantage of optical OFDM is that it can cope with virtually unlimited amount of inter symbol interference (ISI). In high-speed optical transmission systems, ISI is caused for instance by chromatic dispersion and polarization mode dispersion (PMD), which are serious issues in long-haul systems whose bit rate is higher than 40 Gbit/s.

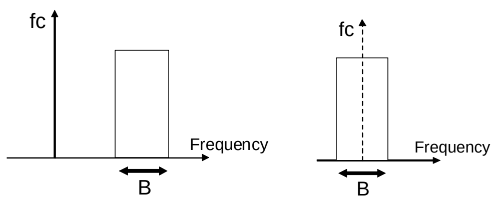
In this paper some of the basics of an optical OFDM system are discussed. Furthermore, high-speed transmission experiments up to 122 Gbit/s are presented

2. Optical OFDM systems

The basic concept behind OFDM is the division of a high bit rate data stream into several low bit rate streams, which are simultaneously modulated onto orthogonal subcarriers. In general, the subcarriers are generated in the digital domain, therefore these systems typically consist of many subcarriers (typically more than 50). In these systems, channel estimation is realized by periodically inserting training symbols [1]. In fiber-optic transmission systems, the OFDM systems where the subcarriers are generated in the optical domain are also proposed. These systems are sometimes referred to as coherent WDM systems [2]. Coherent WDM systems typically have few subcarriers and do not use training symbols, but rely on blind channel estimation instead [3].

3. Optical front end

In optical OFDM systems, the front end of the transmitter consists of an optical modulator, where the OFDM signal is unconverted to the frequency of an optical carrier. The front end at the receiver consists of either a coherent (CO) or a direct detection (DD) scheme. DD-OFDM is realized by sending the optical carrier along with the OFDM band so that direct detection with a single photodiode can be used at the receiver. In a CO-OFDM system, the optical carrier is suppressed at the transmitter and a local oscillator (LO) and optical hybrid is required such as shown in Fig. 2. The superior performance of CO-OFDM with respect to optical signal-to-noise ratio requirements, PMD tolerance and spectral efficiency makes it an excellent candidate for long-haul transmission systems, whereas DD-OFDM, which requires fewer components at the receiver than CO-OFDM, is more suitable for cost-effective short reach applications.



(a) DD-OFDM (b) CO-OFDM

Fig. 1 Optical spectrum of Optical OFDM.

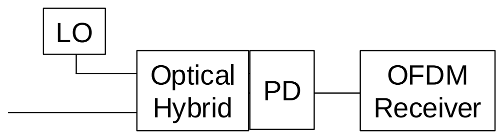


Fig. 2 Receiver configuration for CO-OFDM.

4 Optical OFDM transmission experiments

4.1 100-Gbit/s transmission experiment

Recently, in both CO-OFDM [4] and DD-OFDM [5,6] systems,100 Gbit/s-class transmission experiments were demonstrated. In order to increase the bit rate to 100 Gbit/s-class, a polarization-division-multiplexing (PDM) is indispensable for a reduction of the signal bandwidth which determines the required bandwidth of components in the transmitter and receiver. In PDM-OFDM demonstrations, polarization components are separated digitally by multiple-input and multiple-output (MIMO) processing [7]. In order to apply the MIMO processing in DD-OFDM systems, an optical hybrid at the receiver [5] or a set of two carriers together with specially designed training signal patterns [6] were introduced.

Our group reported CO-OFDM transmission of 10 x 122 Gbit/s over 1,000-km SSMF without any dispersion compensation [4]. In this experiment, the 122-Gb/s OFDM signal consists of two polarization-multiplexed signals with four subcarrier-multiplexed OFDM bands each. Together with a non-rectangular 8 QAM constellation (Fig.5(a)) used for symbol mapping, the 122-Gb/s OFDM signal can be packed in a 23-GHz bandwidth as shown in Fig. 3. At the receiver, the signal is coherently detected with an optical hybrid and an external cavity laser. A real-time digital storage oscilloscope is used to sample the outputs of the optical hybrid and the acquired data is post-processed off-line. Polarization de-rotation can be realized through MIMO processing and RF-aided phase noise compensation is also implemented [8]. After 1,000-km transmission, the obtained BER values for all channels are well below the threshold of a concatenated FEC code with 7% overhead. Along the whole link, the OFDM signal is continuously detectable demonstrating a dispersion tolerance of more than 18,500 ps/nm. Such a large dispersion tolerance is attractive for high speed transmission systems as it eliminates the necessity of inline dispersion compensation.

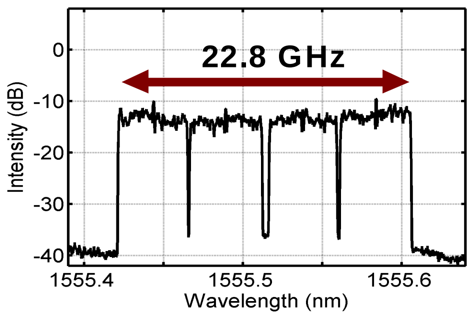


Fig. 3 Optical spectrum of 122-Gbit/s OFDM signal.

4.2 Highly spectral efficient transmission experiment

OFDM is also suitable for highly spectral efficient transmission systems, since it offers distinct advantages compared to other formats. First of all, OFDM is easily scalable to higher level modulation formats. Secondly OFDM has negligible linear crosstalk between channels because of its well defined spectral shape inherently.

Fig. 4 shows the achieved spectral efficiency in recent demonstrations of DWDM transmission with a channel bit rate of higher than 40 Gbit/s. In a wide rage of distances, the highest spectral efficiency is achieved with optical OFDM, which clearly indicates the suitability of OFDM in highly spectral efficient transmission systems.

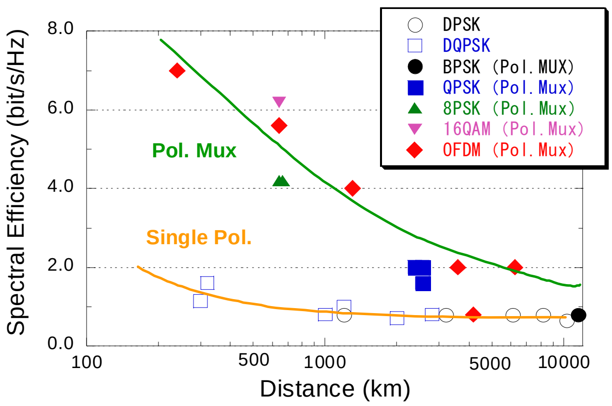
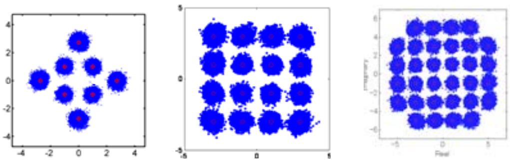


Fig. 4 Recent DWDM transmission experiments.

Recently, our group reported CO-OFDM transmission of 8 x 65 Gbit/s over 240-km SSMF with spectral efficiency of 7.0 bit/s/Hz. [9]. In this experiment, the use of higher level modulation format of 32-QAM (Fig.5(c)) enables to increase the bit rate in a PDM-OFDM band to 65 Gbit/s, which includes a training symbol (6.3%), cyclic prefix (1.9%) and FEC overhead (7%). This results in a net bit rate of 56 Gbit/s and wavelength-division-multiplexing the 56-Gbit/s signals with an 8 GHz spacing, a spectral efficiency of 7.0 bit/s/Hz was achieved. The achieved spectral efficiency is the highest in WDM transmission with channel bit rate of higher than 40 Gbit/s



(a) 8-QAM (b) 16-QAM (c) 32-QAM

Fig. 5 Constellation of subcarrier modulation.

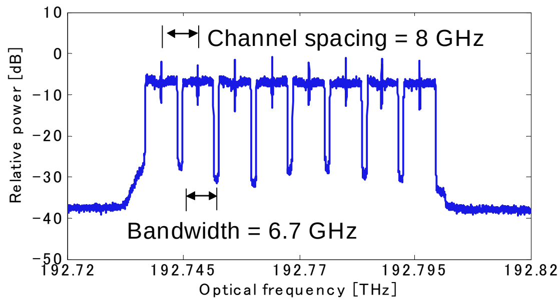


Fig. 6 Optical spectrum in 8 x 65-Gbit/s WDM transmission experiments

Conclusions

In this paper, some important aspects of OFDM fiber-optic transmission systems have been discussed. With CO-OFDM, a transmission with high bit rate (122 Gbit/s) and high spectral efficiency (7.0 bit/s/Hz) is demonstrated without any dispersion compensation. These demonstrations show the suitability of optical OFDM in high-speed transmission systems with high spectral efficiency.

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