100 Gbit/s Transmission using Single-Band Direct-Detection Optical OFDM

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Abstract: We experimentally demonstrate a single-band direct-detection polmux OFDM system using novel colorless transmitter and pol-mux receiver architectures. We transmit 100 Gbit/s over 500 km of standard SMF with a spectral efficiency of 3.57 bit/s/Hz.

OCIS codes: (060.2330) Fiber optics communications; (060.4080) Modulation.

1. Introduction

Previously, Optical Orthogonal Frequency Division Multiplexed (O-OFDM) systems operating at >100 Gbit/s have been demonstrated; however, these have all relied on: a) coherent detection [1] and b) multiplexing several electrical OFDM bands [2] either in the RF or the optical domains [3], [4], [5] to overcome the speed limitations of the Digital to Analog converters.

In this paper, we experimentally demonstrate a 100 Gbit/s optical-OFDM system using: a) a direct-detection receiver [6] and b) a single electrical OFDM band (per polarization) modulated onto a single optical carrier. This is the fastest direct-detection OFDM system to date [7] and offers a simpler transmitter architecture compared with banded systems. The transmitter and receiver were built using commercial parts and commercial Arbitrary Waveform Generators (AWGs) and a Digital Serial Analyzer. Several novel features were included into the transmitter and receiver design to enable high-bandwidth transmission and polarization demultiplexing.

2. System Design

The system design is shown in Figure 1. The transmitter is designed to use as few optical and RF parts as possible: there are no optical comb generators, optical demultiplexers or RF mixers in the transmitters. This requires the in-phase (I) and quadrature (Q) Digital-to-Analog Converters (DACs) to carry the full data rate, rather than building up the OFDM signal from lower-rate electrical signals using RF or optical combiners [2]. The transmitter produces a band of OFDM subcarriers, centered on the laser's line, and an offset virtual carrier, to allow direct-detection at the receiver. This is similar to previous virtual-carrier techniques [8]; however, the virtual carrier is created from an RF signal that is added to the I and Q DACs' outputs (presented at OFC2009 [9] in a 24-Gbit/s system), rather than digitally, which would double the required DAC bandwidths and sample rates. Because no optical filters are used at the transmitter, it can be tuned to any wavelength (it is 'colorless').

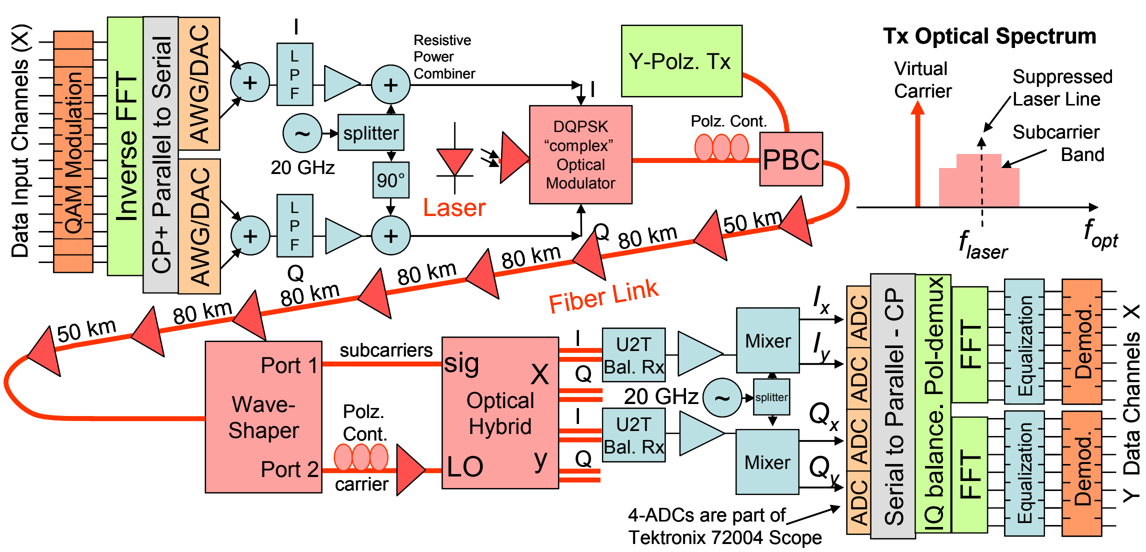

Fig. 1. Schematic diagram of the single-band direct-detection polarization-multiplexed OFDM system.

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The receiver uses an optical filter to split the transmitted carrier from the subcarrier band [10], so a polarization-diverse receiver can be used to demultiplex the polarization-multiplexed signals. Balanced-photodiodes are used to cancel the *subcarrier*×*subcarrier* noise normally associated with direct-detection systems. This allows the usual 'gap' [6] between the carrier and subcarrier bands to be reduced, increasing the spectral efficiency of the system.

The prototype system uses two commercial 20GS/s Arbitrary Waveform Generators (first-generation Tektronix AWG7102s); one to generate the I signal and one for the Q signal. Rather than using their internal interleavers, a flatter response was obtained using 30-GHz resistive power combiners. The two generators are locked to a common clock and a common trigger source, to maintain synchronism between the I and Q signals. The data is transmitted as 16-QAM on 498 subcarriers and 4-QAM on 300 subcarriers. 224 subcarriers are unmodulated to provide a sufficient frequency guard band for the image-rejection filters to operate within. The optical OFDM signal has a double-sided bandwidth of 16 GHz. Because this is requires 8-GHz electrical bandwidth, which is beyond the specified 5.6 GHz bandwidth of the DACs, strong digital pre-emphasis is used. A cyclic prefix of ¼ was used to match a delay line used to decorrelate the transmitted polarizations; although a much-shorter CP could be used in a real system using independent transmitters for the two polarizations.

The AWGs' outputs are fed though 10-GHz low-pass filters, amplified, then resistively-combined with I and Q components of a 20-GHz RF carrier. This provides a 12-GHz gap between the subcarrier band and the carriers, less than conventional direct-detection OFDM systems, which would require a gap equal to the subcarrier bandwidth (16 GHz). The outputs of the resistive combiners are amplified and fed to a Sumitomo T-SBXI.5-20P 40-Gbps DQPSK optical modulator. A Photonetics Tunics laser, tuned to 1550 nm and optically amplified, feeds the modulator. The modulator is biased at its null, so the OFDM voltage signal maps to the optical field, and the laser line is suppressed. The virtual carrier is created by the 20 GHz sine/cosine waves added to the OFDM signal bands before the modulator. The Y-polarization transmitter was emulated by splitting and delaying the output of the X-polarization transmitter. In a real system, the Y-polarization transmitter is a replica of the X-polarization hardware but without the virtual carrier injection, as the receiver can use the X-polarization's carrier is an adaptive polarization controller is used before the optical hybrid.

The fiber plant is one span of 50-km S-SMF fiber, 5-spans of 80-km, and one span of 50-km with no dispersion compensation. EDFAs are used between each span. The output of the fiber is optically-preamplified and passed through a programmable optical filter (Finisar 'Waveshaper') which separates the transmitter carrier from the OFDM sideband. The carrier is boosted [11] by an optical preamplifier and is fed into a Kylia 2×4 optical hybrid which can produce I and Q outputs in the X and Y polarizations. Because the carrier is offset from the sideband, use the hybrid as a heterodyne receiver, so only its I outputs in the X and Y polarizations are required. These are fed into two U^2T 40-GHz balanced photodetectors, one for each polarization. The photodetectors' intermediate-frequency outputs are in the range 12 GHz to 28 GHz. These are amplified then downconverted using wideband IQ mixers with a 20-GHz local oscillator to produce complex baseband signals in the range +/- 8 GHz. These I_x, Q_x, I_y, Q_y, signals then fed to a Tektronix 72004 4-channel 20-GHz 50-Gsample/s oscilloscope. The samples from the scope are analyzed using MATLAB, which includes algorithms for *I-Q* imbalance correction [2], polarization demultiplexing, channel equalization and QAM decoding.

3. Experimental results

Figure 2 shows the transmitted optical spectrum obtained using an Agilent High-Resolution Spectrophotometer (HRS). The spectrum has a 16-GHz subcarrier band, centered upon the suppressed laser line. The subcarrier band is stepped because of the 16-QAM modulation requires a higher OSNR than the 4-QAM. The virtual carrier is 20-GHz below the centre of the subcarrier band. An image of the virtual carrier is at +20 GHz, which is suppressed by 5-dB. The 12-GHz gap between the subcarrier band's lowest frequency and the virtual carrier is necessary for the optical filters to separate the carrier and sideband at the receiver: the WaveShaper has approximately 7.5 GHz resolution.

Figure 3 shows the received and equalized constellations for the 4-QAM and 16-QAM signals. The X and Y-polarization data is overlaid. Overall we measured a BER of 1.8×10^{-3} with an OSNR of 23.5 dB (0.1 nm resolution).

4. Discussions and Conclusions

We have presented a new design for a for a direct-detection optical OFDM system that can support 100-Gbit/s transmission. With improvements in DAC analog bandwidth, the system could be increased to 120 Gbit/s including overheads. There are a number of novel features. Firstly, at the transmitter, a virtual carrier is generated by adding sine and cosine RF signals to the baseband I, Q signals. This reduces the sampling rate for a given RF bandwidth. Furthermore, the electrical signal is generated in a single band using, so it does not require RF or optical methods of multiplexing. A direct-detection receiver is used to receive and separate the polarization-multiplexed signals. This is based on a heterodyne coherent receiver design; however, the local oscillator of a coherent receiver is replaced with the carrier generated by the transmitter. The balanced photodiode design means that *subcarrier×subcarrier* noise is suppressed, which allows the frequency gap between the carrier and the subcarriers to be reduced, increasing spectral efficiency. Also, the carrier is boosted at the receiver, which improves the OSNR performance of the system. The use of a transmitter-generated carrier for detection has the advantage that laser phase noise is less critical than in coherent-OFDM systems that do not use a pilot tone for phase noise cancellation [12].

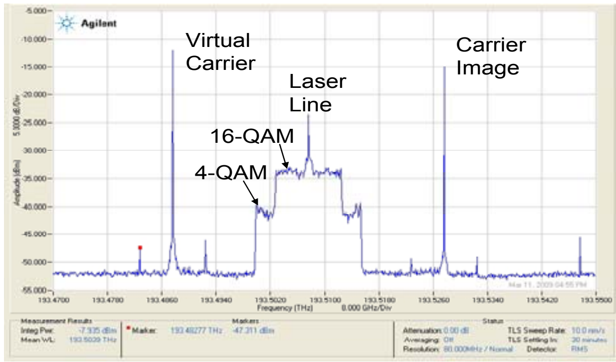

Fig. 2. Received optical spectrum.

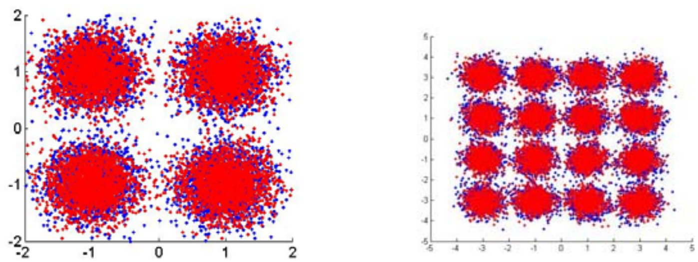

Fig. 4. Received and equalized constellations (4-QAM and 16-QAM).

Acknowledgements
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