FPGA-Based Optical Transmitters for Electronic Predistortion and Advanced Signal Format Generation

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Abstract: We describe an optical transmitter, based on field programmable gate arrays, carrying out real-time DSP at 21.4 GSa/s. We implemented electronic predistortion at 10.7 Gb/s, and 8.35 Gb/s optical orthogonal frequency division multiplexed (OFDM) signal generation.

1. Introduction

The continued rapid progress of digital electronics, following Moore's law, is allowing increasingly powerful digital signal processing (DSP) techniques to be used for the generation and detection of advanced signal formats, such as orthogonal frequency division multiplexing [1], and for the mitigation of transmission impairments at multi-Gb/s line-rates [2]. Application specific integrated circuits (ASIC) offer the best performance, but suffer from long development times, inflexibility and high development costs. For research, development and prototype construction, field-programmable gate arrays (FPGA) are an attractive alternative, and we have assessed their use to implement advanced programmable optical transmitters. This paper describes our recent research results using these devices for electronic predistortion (EPD) and for the generation of optical orthogonal frequency division multiplexed signals using real-time DSP at a sample rate of 21.4 GSa/s.

2. Transmitter design

A schematic of the transmitter designed and constructed at UCL is shown in Fig. 1. The bit sequence to be transmitted is stored in read only memory (ROM) on each FPGA, and pattern synchronisation pulses passed between the FPGAs ensures pattern alignment between them. The optical signal is generated using a Cartesian Mach-Zehnder modulator (MZM) with an integrated laser operating at 1554.94 nm. The MZM is driven by two drive signals, separately generating the real and imaginary parts of the optical signal. These drive waveforms are calculated in real-time by two Xilinx Virtex-4 FPGAs (4VFX100) and are passed as sixteen 5.35 Gb/s data streams from each FPGA to a 4-bit resolution digital-to-analog converter (DAC), which time division multiplexes the signal to 21.4 GSa/s. A detailed description of the design is given in [3].

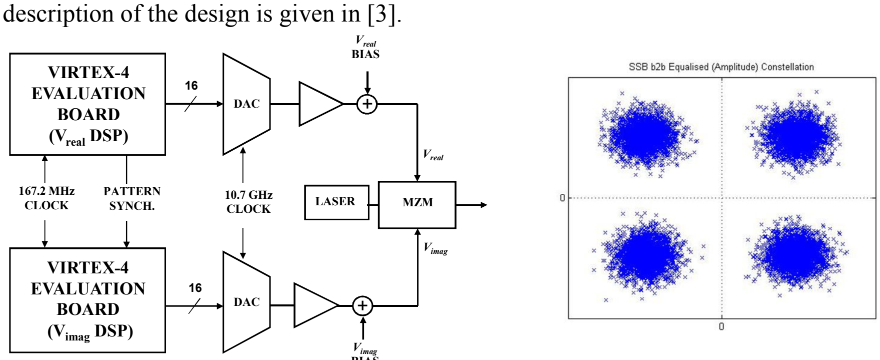

Fig. 1 Left: Transmitter design. Right: Constellation of an 8.35 Gb/s optical OFDM signal generated using the transmitter.

3. Implementation of electronic predistortion

The first set of experiments we performed were designed to investigate the effectiveness of chromatic dispersion compensation by signal predistortion at 10.7 Gb/s. To achieve this, circuits implementing finite impulse response (FIR) filters with 55-taps were programmed onto the FPGAs. The internal clock rate on the FPGA was 167 MHz, and to achieve the 21.4 GSa/s rate, the DSP was carried out with 128 FIR filters, operating in parallel, with identical tap weights.

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Using a recirculating loop, comprising an 80 km span of standard SMF (dispersion value D = 17 ps/(nm.km)) without optical dispersion compensation, transmission experiments were performed with predistorted 10.7 Gb/s binary on-off keyed signals carrying a 2^7 DeBruijn bit sequence. The results are plotted in Fig. 2. At a BER of 10^{-3}, required optical signal-to-noise ratios (measured in a 0.1 nm bandwidth) of 11.5 dB and 12.6 dB were measured for 800 km and 1200 km transmission distances. A detailed discussion of the results can be found in [3]. Further experiments carried out using commercial 6-bit DACs and real-time DSP implemented with FPGAs, demonstrating simultaneous dispersion and self-phase modulation compensation were recently reported in [4].

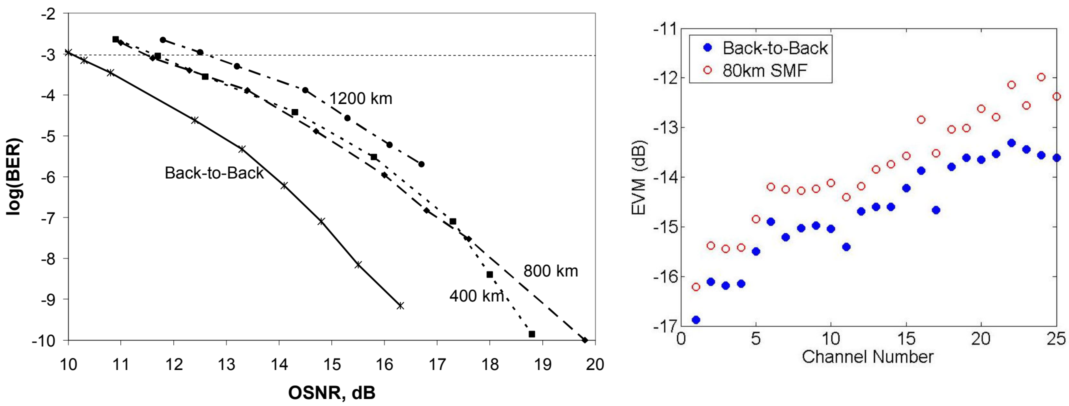

Fig. 2 Left BER versus OSNR for 10.7 Gb/s EPD signals [3], Right: Measured EVM for 8.35 Gb/s OFDM signals

4. Optical orthogonal frequency division multiplexing

The second set of experiments we performed demonstrated the generation of optical orthogonal frequency division multiplexed (OFDM) signals, a single sideband 8.35 Gb/s signal with direct detection, using the approach described in [1]. An optimized 128-input inverse fast Fourier transform (IFFT) core operating at 167 MHz was computer generated using a tool developed in the SPIRAL project at Carnegie Mellon University [5], and programmed into the FPGA in place of the FIR filters used for the EPD experiments. Modulation circuits and clipping/scaling circuits were used before and after the IFFT core respectively. A double sideband OFDM signal was generated, and an optical filter was used to remove the unwanted sideband. All other aspects of the transmitter remained unchanged. Twenty five sub-channels over the frequency range 4-8 GHz, were used to carry a 2^{15} DeBruijn bit sequence, using the QPSK format. A single photodiode followed by a 50 GSa/s real-time oscilloscope were used to detect and store the transmitted signal, and equalization and decoding were carried out offline. The measured constellations of all 25 channels after equalization of their amplitudes are plotted in Fig. 1, the four points of the QPSK signals being clearly visible. The error vector magnitudes (EVM) [6] of the sub-channels are plotted in Fig. 2. Due to the roll-off of the DAC, the higher frequency channels had lower amplitude, and hence lower SNR. The EVM varied from -16.8 dB to -13.2 dB (corresponding to BER values 10^{-12} to 10^{-5}) across the channels. Transmission of the signal over 80 km of standard SMF was also demonstrated with the measured EVM values plotted in Fig. 2.

In conclusion, we have designed and constructed an optical transmitter, based on field programmable gate arrays, carrying out real-time DSP at 21.4 GSa/s, and have demonstrated its versatility as a research and development tool by using it to implement electronic predistortion at 10.7 Gb/s, and 8.35 Gb/s optical orthogonal frequency division multiplexed (OFDM) signal generation.

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