Single Channel, 200 Gb/s, Chromatic Dispersion Precompensated 100 km Transmission Using an Optical Arbitrary Waveform Generation Based Optical Transmitter

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Abstract: This paper presents single channel, 200 Gb/s, 20-bit DPSK packets generated by an optical arbitrary waveform generation based optical transmitter with chromatic dispersion precompensation, and their transmission through 100 km of single-mode-fiber and recovery.

OCIS codes: (320.5540) Pulse Shaping; (060.1660) Coherent Communications; (320.7100) Ultrafast Measurements.

1. Introduction

Optical arbitrary waveform generation (OAWG) transmitters (OAWG transmitters) are a promising technology to enable sustained Internet bandwidth growth [1, 2]. Through parallel modulations of spectral intensity and phase of individual optical frequency comb (OFC) spectral lines, extremely high bandwidth transmissions become possible while maintaining the data integrity on a single wavelength channel. An OAWG transmitter can generate a high bandwidth single channel signal in any modulation format including on-off keying (OOK) and differential phase shift keying (DPSK) [2], or can generate full spectra of subcarrier modulation formats such as orthogonal frequency-division multiplexing (OFDM) [3] and coherent wavelength division multiplexing (CoWDM) [4].

Fig. 1 shows the principle of an OAWG transmitter for the static case, which is based on line-by-line shaping of individual comb lines from a comb source to generate repetitive arbitrary waveforms [1, 5]. A transform limited comb source consists of discrete frequency modes with spacing f_r, which is a short pulse in the time domain that repeats every $1/f_r$. The comb source is then spectrally demultiplexed separating each comb line onto a separate output. Next, each comb line is modulated in both intensity and phase, and recombined with a spectral multiplexer to yield the desired waveform.

Precompensation for an arbitrary amount of chromatic dispersion (CD) in an OAWG transmitter becomes possible by adjusting the spectral phase of the desired waveform by an amount inverse to the fiber link dispersion [2]. In contrast, OFDM and CoWDM systems rely on many orthogonal low speed subcarriers and digital signal processing (DSP) to manage dispersion [3, 4]. Other transmission schemes utilize dispersion compensating fiber or rely on an optical phase conjugation in the middle of the fiber link, which is based on a nonlinearity [6]. Compensation of CD and fiber nonlinearities are relatively difficult to simultaneously compensate in the receiver. Implementing CD precomensation in an OAWG transmitter enables a simpler receiver design that only requires compensating for fiber nonlinearities. This paper builds on our previous work in [2] by shaping more than four times the number of comb lines and compensating for ten times the amount of chromatic dispersion using an OAWG device with narrower channel spacing.

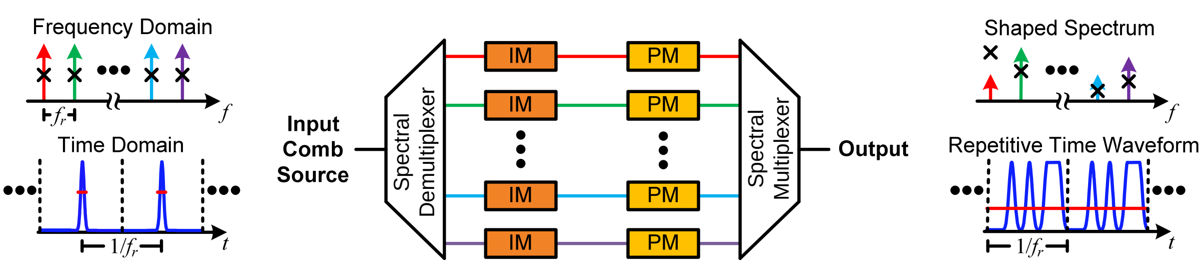

Fig. 1. OAWG methodology involves the manipulation of spectral intensity (↑) and phase (✕) of N individual comb lines in both to create desired temporal intensity (blue) and phase (red). In static OAWG, the shaped waveform repeats every $1/f_r$. IM: intensity modulator, PM: phase modulator.

In the dynamic OAWG case, generation of arbitrary waveforms occupying many OFC periods becomes possible through modulation of the spectral intensity and phase at bandwidths equivalent to the comb spacing, f_r [1]. The Fourier transform of a long waveform occupying N of $1/f_r$ periods is spectrally demultiplexed into spectral slices each with a bandwidth of f_r. The inverse Fourier transform of a spectral slice yields the time domain modulations for the corresponding comb line, which only require a bandwidth of f_r. This technique is bandwidth scalable without any increase in bandwidth of the required electronics. Work is in progress to realize dynamic OAWG on the InP platform [7, 8].

2. Experiment

Fig. 2 shows the experimental arrangement, which consists of an OAWG transmitter and receiver. The OFC has 39 comb lines within 20 dBc at 10 GHz spacing (f_r) for a total bandwidth of 380 GHz. In this case the OFC is generated by amplitude and phase modulation of a cw laser using a dual drive Mach-Zehnder modulator enabling the creation of a spectrally flat OFC [9]. The silica based 10 GHz waveform shaper is capable of 64 channel, thermal-optic spectral intensity and phase modulation. The computer based digital signal processing (DSP) determines the necessary modulator driving voltages to create the desired waveform with optional CD precompensation [1]. This is accomplished by first defining a train of unit impulses evenly spaced over the OFC period, with each impulse set to the intensity and phase of a modulation format symbol. Next, a band-limited raised cosine modulation filter (a type of Nyquist filter) with $\beta = 1$ is defined. Nyquist filters have the added advantage of zero intersymbol interference (ISI) at adjacent symbol locations. The raised cosine modulation filter is applied to the symbol train to define the shape of each bit with minimized time domain ripple. At this point, optional CD precompensation can be incorporated by applying the inverse of the transmission link dispersion profile. Finally, the spectral intensity and phase values are converted to electrical voltages used to drive the intensity and phase modulators.

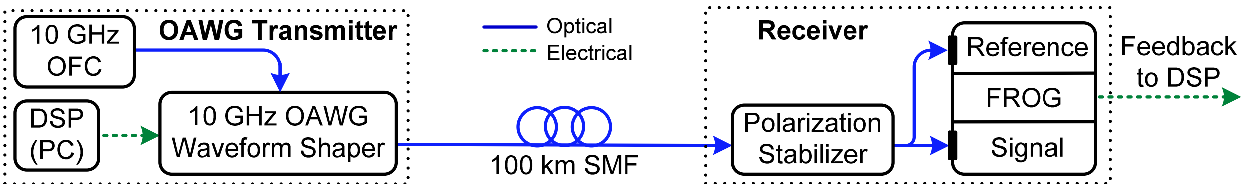

Fig. 2. Experimental arrangement.

The receiver is based on frequency resolved optical gating (FROG), which is an averaged measurement technique capable of characterizing intensity and phase of a repeated waveform [10]. Feedback from the FROG enables fine tuning of the desired waveform in an iterative manner. Complete characterization of an OAWG device eliminates the need for iterations in a real system.

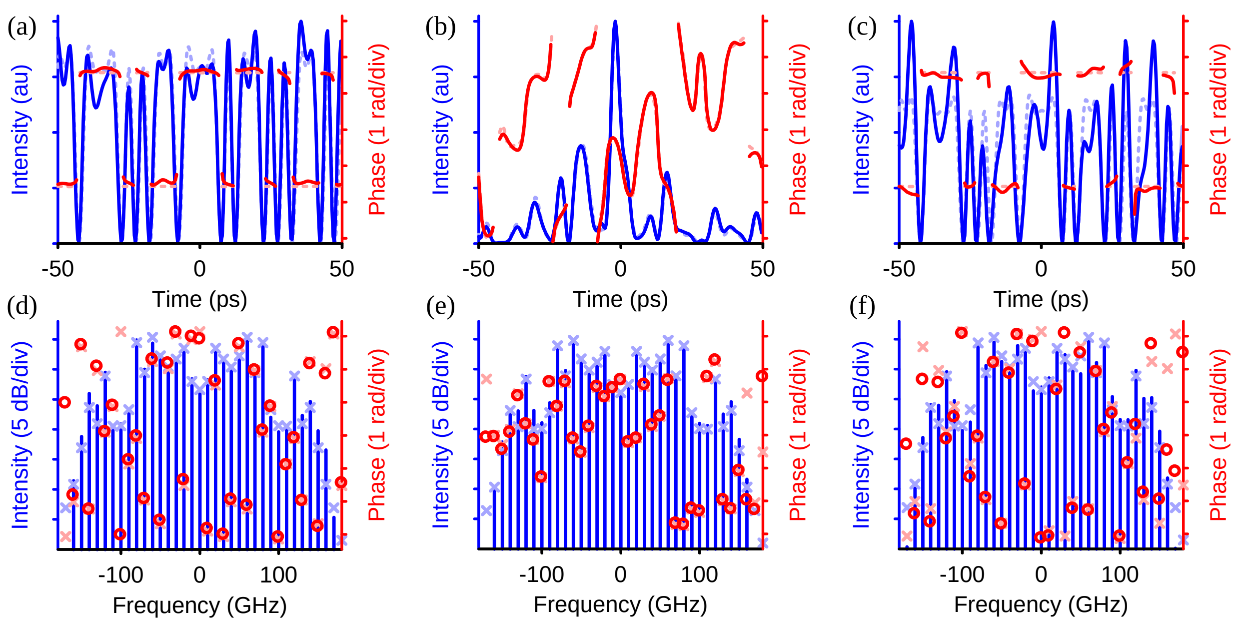

Fig. 3. Measured temporal intensity (blue) and phase (red) for the 20-bit DPSK waveform (a) without CD precompensation measured prior to transmission, (b) with CD precompensation measured prior to transmission, and (c) with CD precompensation measured after transmission. Target values dashed. Measured spectral intensity (stems) and phase (circles) for (d) without CD precompensation measured prior to transmission, (e) with CD precompensation measured prior to transmission, and (f) with CD precompensation measured after transmission. Target values ("x").

Fig. 3(a,d) shows a 20-bit DPSK packet shaped without CD precompensation and measured prior to transmission. The π-phase shifts represent "1" bits and no phase shift represents a "0" bit. The zero levels at the π-phase shifts are due to passing through the origin when changing constellation points and the uneven ones level in-between π-phase shifts is a result of the band-limited raised cosine modulation function used in the DSP [1]. Approximately 8 iterations of phase feedback were required to achieve phase errors of ± 0.2 across the central 35 comb lines. Fig. 3(b,e) shows the 20-bit DPSK packet measured prior to transmission with precompensation for 100 km of SMF with 1675.2 ps/nm of dispersion and 4.83 ps/nm^2 of dispersion slope. The waveform strongly resembles the target, but is not easily recognizable as a DPSK signal. Fig. 3(c,f) shows the CD precompensated, 20-bit DPSK packet measured after transmission. In Fig. 3(c) the π-phase changes closely match the target phase, while there is some intensity fluctuation due to errors in waveform shaping and CD precompensation.

Fig. 4 shows computer generated pseudo-eye diagrams of experimentally measured DPSK waveforms assuming a balanced receiver with sufficient bandwidth. Fig. 4(a) is a pseudo-eye diagram of a DPSK waveform without CD precompensation prior to transmission and without CD precompensation. Fig. 4(b) and Fig. 4(c) show pseudo-eye diagrams of DPSK waveforms with CD precompensation before and after transmission, respectively. The eye after transmission is open, but slightly less open than Fig. 4(a) due to finite tolerances in the waveform shaping CD precompensation in addition to contributions from fiber nonlinearity. Further improvements are expected by incorporating adaptive precompensation scheme with considerations for fiber nonlinearity..

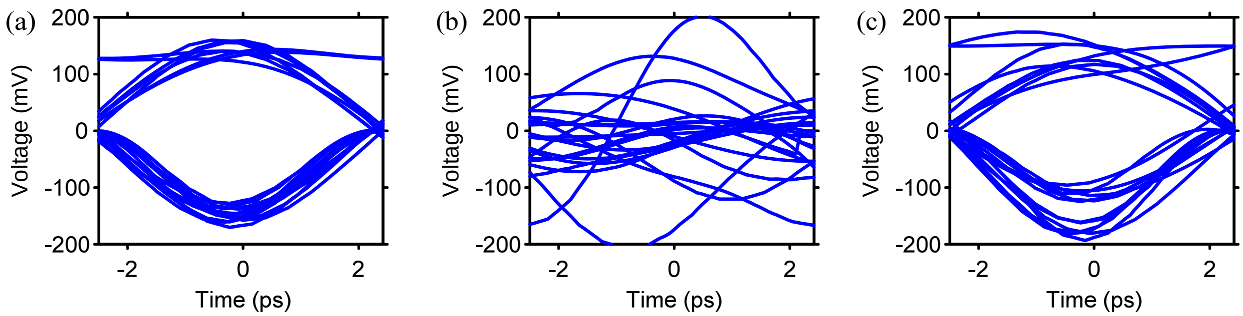

Fig. 4. Pseudo-eye-diagrams of measured data assuming a receiver conversion of 50 V/W and 1 mW of average power. DPSK waveforms (a) without CD precompensation prior to transmission, (b) with CD precompensation prior to transmission, and (c) with CD precompensation after transmission.

3. Conclusion

This paper outlines the potential for high-speed single channel optical transmission systems by means of OAWG transmitter based signal generation with CD precompensation. An example of a 200 Gb/s, 20-bit DPSK waveform with CD precompensation through 100 km of SMF is presented. Realization of dynamic OAWG by exploiting photonic integration technology based on materials such as InP or $LiNbO_3$ will allow transmission of infinitely long sequence datagrams with arbitrary modulation formats.

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