400-Gb/s Modulation-Format-Independent Single-Channel Transmission With Chromatic Dispersion Precompensation Based on OAWG

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Abstract—This letter demonstrates the efficacy of an optical arbitrary waveform generation (OAWG) transmitter in generating high-bandwidth, single-channel optical waveforms with precompensation overcoming chromatic dispersion. Specifically, 20-bit, 200-Gb/s differential phase-shift keying and 40-bit, 400-Gb/s quadrature phase-shift keying packets are precompensated for the 1675.16 ps/nm of dispersion and 4.833 ps/nm² of dispersion slope present in 100 km of single-mode fiber, and successfully recovered after transmission. The repetitive waveform packets were generated using static OAWG methodology, with a pair of silica arrayed-waveguide gratings through line-by-line pulse shaping.

Index Terms—Arrayed-waveguide grating, dispersion precompensation, Fourier synthesis.

I. INTRODUCTION

HIGH-CAPACITY transmission systems must overcome problems such as bandwidth scalability and chromatic dispersion (CD) in order to support an increasing number of high-bandwidth Internet applications. Recently, digital coherent receivers have facilitated the use of advanced modulation formats with an increased number of bits per symbol in support of high spectral efficiency. Research is underway to explore optical arbitrary waveform generation (OAWG)-based optical transmitters, which use parallel modulations of optical frequency comb (OFC) lines to create high-bandwidth communications waveforms with electronic precompensation for CD [1], [2]. These modulations exploit intensity and phase (or in-phase and quadrature-phase) modulators that convert an electrical voltage into the intensity and phase (or in-phase and quadrature-phase) values of the optical field. Coherent wave-length-division multiplexing (CoWDM) [3], [4] and orthogonal frequency-division multiplexing (OFDM) [5], other methods of high-bandwidth transmission being explored, rely on many low-speed orthogonal subcarriers to increase transmission bandwidth while mitigating the effects of CD.

In particular, an OAWG transmitter (Fig. 1) functions by first spectrally demultiplexing OFC lines onto separate waveform outputs. Next, electrically driven optical modulators separately modify each comb line in both intensity and phase to create the desired spectral profile predetermined by digital signal processing (DSP). A spectral multiplexer then combines the modulated OFC lines to produce the complete waveform spectrum, which relates to the time domain via Fourier transform. An OAWG transmitter is bandwidth scalable by increasing the number of OFC lines and using spectral demultiplexers and multiplexers with a sufficient number of ports, which does not require increased modulator bandwidth. The OAWG transmitter can create waveforms in any modulation format, including single-channel differential phase-shift keying (DPSK), quadrature phase-shift keying (QPSK), ultra-broadband CoWDM, or OFDM waveforms.

An OAWG transmitter has two distinct modes of operation: static OAWG and dynamic OAWG. In static OAWG, the parallel modulations on each OFC line are very slow compared to the OFC line spacing. The static OAWG transmitter produces waveforms that repeat at the repetition rate of the comb source. The duration of the output waveforms is defined by the inverse of the OFC repetition rate, and the smallest temporal feature is the inverse of the OFC bandwidth. Static OAWG requires that shaped waveforms have an integer number of symbols and do not have a temporal amplitude or phase discontinuity at the boundary between adjacent waveforms (other than those related to a change in symbol value). In this letter, we build on previous work [1], [2] and demonstrate static OAWG-based CD precompensation to the transmission of 20-bit, 200-Gb/s DPSK and 40-bit, 400-Gb/s QPSK waveforms through 100 km of single-mode fiber (SMF).

Dynamic OAWG overcomes the time duration limitation of static OAWG through the generation of large bandwidth waveforms, by using many moderate (~10 GHz) modulators. The Fourier transform of a long (many OFC periods) and high-bandwidth waveform can be broken into several spectral slices, each
equal to the OFC line spacing. The inverse Fourier transform of each spectral slice produces continuous temporal real and imaginary modulations of practical bandwidth (≤10 GHz). Spectral recombination of each modulated spectral slice yields a temporal waveform that is much longer than an OFC period.

II. EXPERIMENT

Fig. 1 shows the experimental arrangement consisting of an OAWG transmitter, 100 km of SMF (1675 ps/nm of dispersion and 4.8 ps/nm² of dispersion slope at 1550 nm), and a receiver based on frequency-resolved optical gating (FROG) [6]. The OAWG transmitter consists of a 10-GHz OFC, a 10-GHz OAWG waveform shaper (WS), and DSP to control the WS. The combination of amplitude and phase modulation of CW laser light using a dual-electrode Mach–Zehnder modulator yields a comb source with 35 spectral lines (> −20 dB) over a bandwidth of 350 GHz with 10-GHz spacing [7]. In the time domain, the transform-limited OFC is a ~2-ps pulse repeating every 100 ps. The OAWG WS is composed of a pair of 64-channel silica arrayed-waveguide gratings with electrically driven thermal-optic intensity and phase modulators on each channel [8]. The intensity modulators have an extinction ratio of >20 dB, and the phase modulators are capable of 2π rad phase shifts. Both types of modulators are driven by digital-to-analog convertors (DACs) with 16-bit resolution. The DSP determines the necessary modulator voltages to create data packet waveforms with optional CD precompensation [1]. In this case, 200-Gb/s DPSK and 400-Gb/s QPSK waveforms over 350 GHz (full width) are generated. The DSP defines a series of delta functions in the time domain, with spacing of 1/S, where S is the symbol rate (200 Gsymbol/s). Each delta function is assigned an intensity and phase value for the desired modulation format symbol. The Fourier transform of the modulated delta functions yields the desired waveform spectrum. After the application of a raised cosine filter (a type of Nyquist filter) with a β-factor of 1, truncated at the −14.2-dB points to a bandwidth of 350 GHz, the spectrum becomes bandlimited and the temporal shape of each symbol is defined. Optional CD precompensation can be incorporated by adjusting the spectral phase by an amount inverse to the link transmission function. The resulting spectral intensity and phase values are converted to electrical voltages, used to control the OAWG WS. The modulation format and the bandwidth of the modulation filter determine the spectral efficiency of the ensuing waveform.

The receiver has the ability to measure repetitive waveforms with picosecond resolution. A polarization stabilizer at the front end of the receiver mitigates the effects of environmental polarization variations. The signal is measured with FROG, an averaged measurement technique that yields the intensity and phase of shaped waveforms in both time and frequency domains. Accurate waveform shaping requires comparing the measured intensity and phase to the target values, and updating the modulator settings, in an iterative process. Here, the optical and thermal crosstalk in the OAWG transmitter typically required ten iterations to closely match the target and measured waveforms. However, a practical system could rely on calibration of the OAWG transmitter (including quantification of channel crosstalk effects) to eliminate the need for iterative adjustments.

Fig. 2 shows measured (thin) target (thick) temporal intensity (blue) and phase (red) for the uncompensated 200-Gb/s DPSK packet (a) before and (c) after transmission, and (e) for the CD precompensated 200-Gb/s DPSK packet after transmission. (b) The corresponding measured spectral intensity (stems) and phase (circles) of (a), while (d) and (e) show the spectral phase errors of (c) and (e) relative to the target spectral phase in (b). Target values (‘.”).
pseudo-eye diagrams of the DPSK waveform without CD precompensation prior to transmission and with CD precompensation after transmission, given a balanced receiver with sufficient bandwidth. There is some slight eye closure in the transmitted signal, but the open eye is clearly visible. Fig. 4(c)–(f) shows the in-phase and quadrature pseudo-eye diagrams of the QPSK waveform without CD precompensation measured prior to transmission, and the in-phase and quadrature pseudo-eye diagrams of the CD precompensated QPSK waveform measured after transmission. The open eyes after transmission indicate the potential for successful detection using a QPSK receiver with balanced receivers for the in-phase and quadrature parts. The open pseudo-eye diagrams indicate robustness to systematic problems, but further studies are required to investigate system noise. Also, Fig. 5 shows the constellation diagrams for the QPSK waveform without CD precompensation, measured prior to transmission, and with CD precompensation, measured after transmission.

III. DISCUSSION AND CONCLUSION

This letter has discussed the generation and retrieval of repetitive 20-bit, 200-Gb/s DPSK and 40-bit, 400-Gb/s QPSK waveforms with 100-ps duration through 100 km of SMF with CD precompensation. Future experiments at higher symbol rates and through longer lengths of fiber may require active PMD compensation. Further maturation of the InP platform will enable modulation bandwidths comparable to the spectral resolution of the OAWG devices thus facilitating the development of dynamic OAWG systems [9].

REFERENCES