360-Gb/s Optical Transmitter With Arbitrary Modulation Format and Dispersion Precompensation

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***Abstract*—This letter introduces a versatile data-rate and modulation format transparent optical transmitter for 360-Gb/s transmission based on optical arbitrary waveform generation (OAWG) techniques. An experimental implementation of static OAWG, or line-by-line pulse shaping, with a silica arrayed-waveguide-grating pair waveform shaper, demonstrates creation of repetitive time-domain waveforms representing data packets in on–off keying and differential phase-shift-keying modulation formats with optional precompensation for fiber chromatic dispersion (CD). Transmission of repeated 9-bit 360-Gb/s data packets occupying 680 GHz of total optical bandwidth, with CD precompensation over a 10-km single-mode fiber link, indicates the potential for terabit-per-second operation. These data packets have a spectral efficiency of 0.53 b/s/Hz.**

***Index Terms*—Arrayed-waveguide grating (AWG), dispersion precompensation, Fourier synthesis.**

I. Introduction

OPTICAL arbitrary waveform generation (OAWG) is a technique for generating truly arbitrary waveforms by parallel intensity and phase modulations of individual spectral lines from an optical frequency comb (OFC) [1]–[3]. Applications for customized optical arbitrary waveforms range from light detection and ranging (LIDAR) to coherent control of both chemical reactions and quantum mechanical wave packets [1] to the generation of high-speed data in various modulation formats [4], [5]. Fig. 1 shows how OAWG manipulates an OFC to generate unique, arbitrary waveforms. First, individual comb lines of an OFC with spacing f_r are spectrally demultiplexed onto isolated spatial locations or waveguides (i.e., channels) using a device such as an arrayed-waveguide grating (AWG). Next, simultaneous intensity and phase modulation is applied separately to each comb line. When these modulations are low frequency ($\ll f_r$) or constant it is termed *static* OAWG, which is also known as line-by-line pulse shaping. Finally, the modulated comb lines are multiplexed onto a single spatial location or waveguide, yielding the shaped waveform. The completely specified spectral intensity and phase uniquely defines the time domain waveform via the Fourier transform and the total OFC bandwidth determines the minimum temporal feature size. In static OAWG, the shaped waveform repeats at the OFC repetition rate f_r, and its duration is limited by the OFC period $1/f_r$. However, in *dynamic* OAWG, the modulations are rapidly varying ($\sim f_r$), thereby changing the waveform each OFC period to potentially create extended duration waveforms. By using moderate modulation bandwidth (~10 GHz) with a moderate number of comb lines (~100), very high bandwidth (~1 THz) arbitrary waveform generation is possible. Work is in progress to realize dynamic OAWG on the InP platform [6], [7].

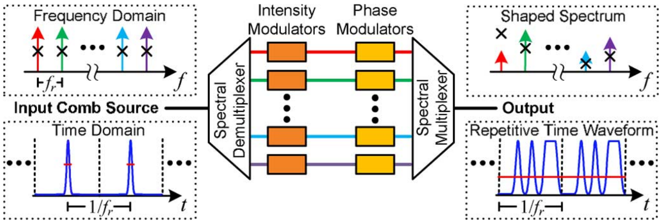

Fig. 1. OAWG methodology involves the manipulation of the spectral intensity (arrows) and phase (×) of N optical comb lines with a total bandwidth of $N \times f_r$, to produce the desired temporal intensity (blue) and phase (red). In static OAWG, the shaped waveform repeats every $1/f_r$.

Previously, static OAWG has been used to position pulses arbitrarily within a temporal window [1], and to produce 8-bit-long 100-Gb/s return-to-zero on–off keying (RZ-OOK) packets [5]. In these cases, only the spectral and temporal intensities of the shaped waveforms were characterized. However, demonstrating high-fidelity waveform generation requires both spectral intensity and phase measurements, which can be achieved with phase-sensitive techniques such as cross-correlation frequency-resolved optical gating (X-FROG) [2].

In this letter, we investigate an optical communications application of OAWG in which static OAWG is used as an optical transmitter to create 9-bit 360-Gb/s data packets in nonreturn-to-zero on–off keying (NRZ-OOK) and nonreturn-to-zero differential phase-shift keying (NRZ-DPSK) modulation formats. Since the OAWG-based transmitter uses a silica AWG pair waveform shaper with kilohertz rate thermooptic-based intensity and phase modulators, it generates multibit data packets which repeat every OFC period. These data packets can be created in any modulation format including on–off keying (OOK), differential phase-shift keying (DPSK), optical orthogonal frequency-division multiplexing [8], or an entire coherent wavelength-division-multiplexing spectrum [9], [10]. The bit rate is independent of the OFC repetition rate, and chromatic dispersion (CD) precompensation can be included in the data packet. The maximum bit rate of the data packets is the product of the OFC bandwidth and the spectral efficiency of the modulation format, and the number of bits

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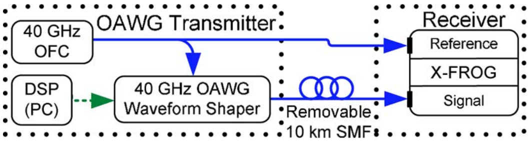

Fig. 2. Experimental arrangement showing the OAWG transmitter used for generation of 9-bit data packets at 360 Gb/s with CD precompensation, and the X-FROG receiver. Optical paths (solid) and electric paths (dashed).

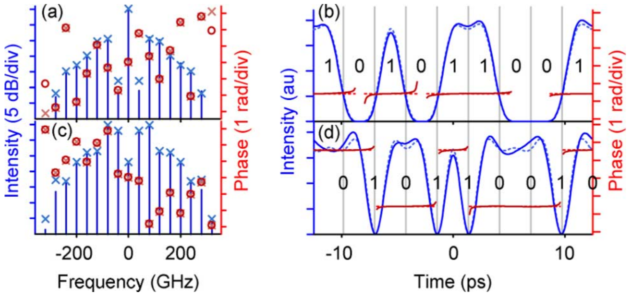

Fig. 3. Measured spectral intensity (stems) and phase (circles) for (a) 101011001 OOK and (c) 001011001 DPSK data packets. Target values ("x"). Measured temporal intensity (blue) and phase (red) for the (b) OOK and (d) DPSK packets. Target values (dashed). Vertical lines differentiate bit periods.

per packet is the bit rate times the OFC period $(1/f_r)$. Adding comb lines to the OFC and corresponding modulators to the OAWG transmitter increases the data packet bandwidth without requiring faster single-channel modulators or electronics. For an OAWG transmitter to be complete, digital signal processing (DSP) is required to determine the proper intensity and phase modulator settings needed to generate the data packets.

II. EXPERIMENT

Fig. 2 shows the experimental arrangement including the OAWG transmitter for data packet generation, consisting of an OFC, a waveform shaper, and an offline DSP (a computer), and the receiver for repetitive data packet measurement using X-FROG. Strong amplitude and phase modulation of a single-frequency 1550-nm laser using a dual-electrode Mach–Zehnder modulator produces an OFC with 17 spectral lines (> -20 dBc, $B = 680$ GHz) spaced at 40 GHz ($f_r = 40$ GHz) [2]. In the time-domain, the OFC output is a pulse train with a 25-ps periodicity and a 1.2-ps transform-limited pulsewidth. The OFC signal is split and one part is sent to a 128-channel AWG-pair waveform shaper with 40-GHz channel spacing. Each channel has intensity and phase modulators providing greater than 20-dB extinction and 2π phase shift. Full control, with 16-bit resolution, over the spectral intensity and phase of the central 17 comb lines (while all other comb lines are fully attenuated) defines a unique temporal waveform with exactly 680 GHz of bandwidth. In the receiver, the OFC is used as a reference pulse for X-FROG [2]. X-FROG is an inherently averaged measurement technique that can completely characterize the intensity and phase in both the time and spectral domains of a repeated waveform (i.e., the data packet). Fig. 3(a) shows an example of a shaped spectrum, and Fig. 3(b) depicts the corresponding temporal waveform.

In this experiment, the software-based transmitter DSP algorithm calculates the intensity and phase modulator settings required to generate spectrally efficient 360-Gb/s repetitive data packets in the NRZ-OOK and NRZ-DPSK modulation formats, including precompensation for CD. The algorithm begins in the time domain by defining a train of nine unit impulses (i.e., delta functions) at a 2.7-ps spacing across a 25-ps window $(1/f_r)$. Each impulse is assigned a temporal intensity and phase value representing a symbol in the specified modulation format. Next, the spectrum of the symbol train is determined by the discrete Fourier transform and then multiplied by a raised-cosine filter (β-rolloff factor of 1) to define the temporal shape of each bit. To apply CD precompensation, the spectrum is also multiplied by the inverse of the transmission link transfer function. At this point, the spectrum of the data packet is completely defined and determines the intensity and phase modulator settings. The raised-cosine filter (a type of Nyquist filter) [11] is band-limited to 680 GHz, and has an impulse response with zero intersymbol interference. In essence, the DSP algorithm defines the 9-bit, 25-ps duration, 680-GHz bandwidth data packets (i.e., 0.53 b/s/Hz spectral efficiency) that the OAWG transmitter can produce.

The back-to-back test of the system used the OAWG transmitter to create 9-bit 360-Gb/s [101011001] OOK and [010110010] DPSK packets, and X-FROG as the receiver. Fig. 3(a), (c) shows a comparison of the measured and target spectra, as determined by the DSP, for the OOK and DPSK packets. Approximately four iterations of waveform shaping and measurement were required to obtain high-fidelity waveforms. The spectral phase error is within ± 0.01 rad of the target values across the central 15 lines. For implementation in a real system, complete calibration of the OAWG transmitter can eliminate the iterations. Fig. 3(b), (d) shows the corresponding time-domain OOK and DPSK waveforms, which are the inverse Fourier transform of the spectra, and closely match their targets in both intensity and phase. The extinction ratio between the "1" bits and "0" bits in the OOK packet is 30 dB. The ripples on consecutive "1" bits are characteristic of the raised-cosine filter's impulse response. In the DPSK packet, a "1" bit is encoded by a π-phase shift between adjacent bit periods and a "0" bit by no phase shift. The highest spectral efficiency DPSK packets have intensity nulls between π-phase transitions since the shortest path between the two states in the complex plane crosses the origin, where the amplitude is zero. Constant intensity DPSK signals require larger bandwidth, thus lowering the spectral efficiency, since the path between the two states follows the unit circle (i.e., a longer path).

The CD precompensation capability of the OAWG transmitter was tested by generating precompensated OOK and DPSK data packets and receiving the packets after transmission through 10-km single-mode fiber (SMF). The SMF dispersion was 168 ps/nm and the dispersion slope was 0.6 ps/nm^2 at 1550 nm. Fig. 4(a), (c) depicts the CD precompensated OOK and DPSK packets measured prior to transmission. Although the precompensated waveforms are complex, the measured intensities and phases match their respective targets. Fig. 4(b), (d) shows the received OOK and DPSK data packets after propagating through 10 km of SMF, which closely resemble the corresponding target waveforms in Fig. 3(b), (d).

Superimposing successive bit periods of the measured data packets in Fig. 4 creates pseudo-eye-diagrams. Assuming direct detection for OOK and balanced detection for DPSK, Fig. 5 shows pseudo-eye-diagrams of waveforms before and after transmission. The eye diagrams of the data packets with

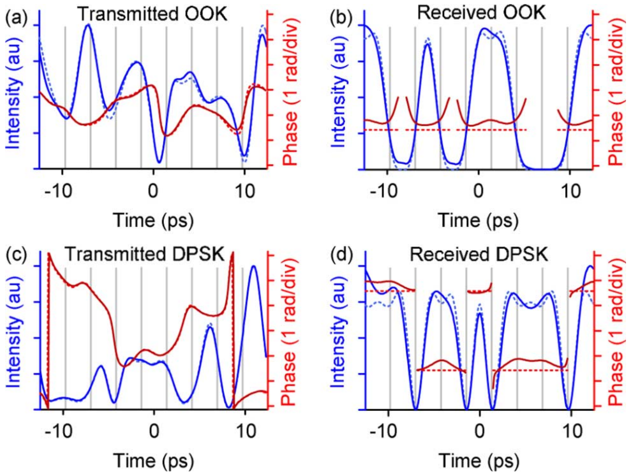

Fig. 4. Precompensated (a) OOK and (c) DPSK packets prior to transmission. Received (b) OOK and (d) DPSK packets after 10-km propagation. Measurements (solid) and targets (dashed).

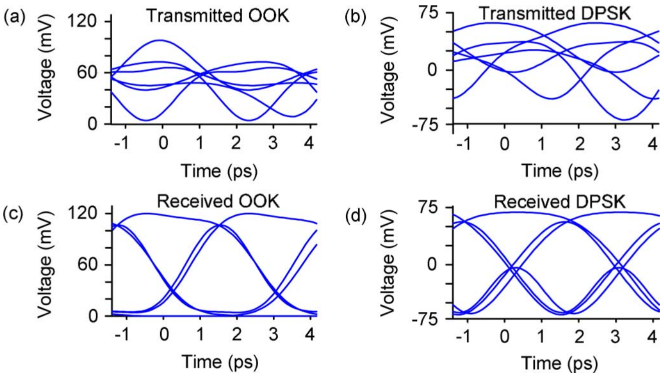

Fig. 5. Pseudo-eye-diagrams from measured CD precompensated data packets assuming a receiver conversion of 50 V/W and 1 mW of average power. OOK packet (a) prior to and (b) after transmission and CD precompensated DPSK packet (c) prior to and (d) after transmission.

CD precompensation measured prior to SMF transmission are completely closed and after SMF transmission, are wide open. The open eye diagrams indicate the potential for real-time receiving, pending a sufficiently fast receiver (~300 GHz). The shapes of the eye diagrams follow the impulse response of the raised-cosine filter. By changing the filter used in the DSP, the shape of the bits is adjusted affecting the eye diagrams.

III. Discussion and Conclusion

Our results demonstrate the concept of an OAWG-based transmitter to generate spectrally efficient, 360-Gb/s data packets in different modulation formats using static OAWG methodology. Generating data packets in different modulation formats with varying bit rates and spectral efficiencies only requires a change to the DSP algorithm. Currently, the inability to rapidly modulate the intensity and phase of each comb line with the silica AWG device limits data packet generation to a repetitive waveform with a duration of $1/f_r$. Dynamic OAWG, in which gigahertz rate modulations are applied to each comb line, can produce extended data packets that span many OFC periods ($\gg 1/f_r$). The modulated comb lines will have large bandwidth ($\sim f_r$), requiring that the AWG multiplexer be gapless (i.e., having overlapping adjacent channels). AWG multiplexers, with specially designed or even configurable passbands, can have flattop transmission and strongly overlapping adjacent passbands, at the expense of increased insertion loss [3]. The procedure to determine the dynamic intensity and phase modulations could work as follows; first, the extended data packet is Fourier transformed to the spectral domain, CD precompensation is applied, and the spectrum is divided into slices of width f_r centered on each comb line. Next, each spectral slice is pre-emphasized for the spectral filter shape. The time-domain modulations on each comb line are then determined by inverse Fourier transforming each band-limited spectral slice. The modulations are continuously defined for the duration of the extended data packet, without requiring guard-bands to allow the modulators to settle between OFC periods. Finally, these band-limited, modulated comb lines are coherently combined by the spectral multiplexer. Further details of dynamic OAWG will be discussed in a future paper [12]. As InP technology matures, implementing dynamic OAWG with modulation bandwidth comparable to the spectral resolution of the devices becomes feasible [6], [7]. Furthermore, electronic speed requirements reduce with decreasing OAWG device channel spacing, potentially allowing scalable terahertz waveform generation.

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