Bandwidth scalable, coherent transmitter based on the parallel synthesis of multiple spectral slices using optical arbitrary waveform generation

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Abstract: We demonstrate an optical transmitter based on dynamic optical arbitrary waveform generation (OAWG) which is capable of creating high-bandwidth (THz) data waveforms in any modulation format using the parallel synthesis of multiple coherent spectral slices. As an initial demonstration, the transmitter uses only 5.5 GHz of electrical bandwidth and two 10-GHz-wide spectral slices to create 100-ns duration, 20-GHz optical waveforms in various modulation formats including differential phase-shift keying (DPSK), quaternary phase-shift keying (QPSK), and eight phase-shift keying (8PSK) with only changes in software. The experimentally generated waveforms showed clear eye openings and separated constellation points when measured using a real-time digital coherent receiver. Bit-error-rate (BER) performance analysis resulted in a BER < 9.8 × 10^-6 for DPSK and QPSK waveforms. Additionally, we experimentally demonstrate three-slice, 4-ns long waveforms that highlight the bandwidth scalable nature of the optical transmitter. The various generated waveforms show that the key transmitter properties (i.e., packet length, modulation format, data rate, and modulation filter shape) are software definable, and that the optical transmitter is capable of acting as a flexible bandwidth transmitter.

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References and links

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1. Introduction

Satisfying the burgeoning demand for Internet bandwidth requires technologies capable of efficiently scaling in bandwidth to support future Tb/s optical transmission standards. Many possible transmission techniques [1–3] achieve high data throughput while using time or frequency parallelism to combat the electronic bottleneck. In particular, coherent wavelength division multiplexing (CoWDM) [4,5] and optical orthogonal frequency division multiplexing (OFDM) [6–8] exploit the use of many orthogonal low-speed subcarriers to generate a large bandwidth transmission. Some optical OFDM approaches implement certain digital signal
processing (DSP) operations (e.g., fast Fourier transform (FFT)) all-optically [9] to reduce the
demand on the supporting electronics and enable real-time OFDM transmission and reception
over large bandwidths [8].

Additionally, to approach optical fiber capacity limits [10], a next generation optical
transmission system will need to efficiently utilize its entire operating bandwidth. This
requires not only employing high spectral efficiency modulation formats, but also increasing
fiber capacity utilization. In conventional fiber networks, the strict ITU grid reserves a certain
fraction of bandwidth for each channel, irrespective of dynamic changes in user demand.
Increases in capacity utilization for future optical networks will require a flexible bandwidth
transmitter that dynamically allocates bandwidth by user demand to further increase the

A technology capable of both bandwidth scalable and flexible bandwidth transmission is
spectrally sliced, dynamic optical arbitrary waveform generation (OAWG), which utilizes the
coherent summation of overlapping independent spectral slices generated in parallel to create
a gapless, complex output spectrum [12,13]. The spectral slice dynamic-OAWG technique
provides for high-fidelity optical waveforms with theoretically unlimited record lengths. This
is in contrast to line-by-line pulse shaping [14], which creates waveforms by adjusting the
amplitude and phase of individual lines of an optical frequency comb (OFC). Thus, the output
waveform is repetitive with a period equal to the OFC period, $T$. If the waveform repetition is
broken by rapidly updating the modulation of individual comb lines, near-infinite bandwidth
is required to completely satisfy the boundary conditions between each period [15,16]. Also,
in the case of rapid update line-by-line pulse shaping, the filtering effects of spectral
multiplexers severely limit the waveform fidelity [15,16] and thus preclude it from use for
advanced format data transmissions.

Furthermore, by aggregating a sufficient number of independent spectral slices, a dynamic
OAWG based coherent optical transmitter (OAWG transmitter) can operate at 1 Tb/s.
Complete control of amplitude and phase over its operating bandwidth enables an OAWG
transmitter to create a broadband single channel signal or to generate a combination of
subcarriers to produce a CoWDM or OFDM transmission. The dynamic nature of the
transmitter also allows seamless reconfiguration between modulation formats over part or all
of its bandwidth. In this sense, an OAWG transmitter is flexible bandwidth capable and can
allocate variable amounts of bandwidth to a particular user, or even implement impairment-
aware adjustments (e.g., manipulate spectral efficiency) upon detecting a change in link
quality [17].

Previously, we introduced the concept of an OAWG transmitter and demonstrated its
bandwidth scalability by generating large bandwidth (400 GHz) data waveforms with
relatively short pattern lengths (100 ps) [12]. Later in [13], we demonstrated the spectral-slice
dynamic-OAWG technique by creating some general (non-data) waveforms with 6-ns
durations and up to 30-GHz of optical bandwidth. This paper focuses on using the spectral
slice dynamic-OAWG technique as a modulation format independent transmitter, and
successfully demonstrates various telecommunications waveforms with significantly extended
pattern lengths (100 ns). An OAWG transmitter, in contrast to others with a similar structure
[4–8], permits single-carrier waveforms or multicarrier waveforms with subcarrier baud rates
completely independent of the subcarrier frequency spacing. This provides greater versatility
in the type of waveforms modulation formats and the number of subcarriers that can be
implemented with a single transmitter structure.

This paper is organized as follows. Section 2 describes the concept of an OAWG
transmitter and the DSP algorithm used to generate the spectral slice modulations. Section 3
presents experimental two slice, 100 ns, 20 GHz results including high spectral efficiency
differential phase-shift keying (DPSK), quaternary phase-shift keying (QPSK), and proof-of-
principle eight phase-shift keying (8PSK) waveforms. Section 3 also shows how an OAWG
transmitter might function as a flexible bandwidth transmitter by adjusting the amount of total
bandwidth utilized or by adjusting the portion of the total bandwidth occupied by the
transmission. Section 3 concludes with bit-error-rate (BER) performance of an OAWG
transmitter for DPSK and QPSK waveforms. Section 4 demonstrates the bandwidth scalability
of an OAWG transmitter through its ability to create three spectral slices and shows 4 ns, 30
GHz QPSK results. Finally, Section 5 concludes the paper.

2. Spectral slice based coherent optical transmitter

An OAWG transmitter creates a large bandwidth optical signal by coherently combining
many overlapping spectral slices to create a bandwidth scalable optical waveform using
currently available electronics [13,18]. This requires a fixed and stable phase relationship
between the independently created spectral slices, which effectively enables an OAWG
transmitter to act as a single broadband modulator without increasing the bandwidth demand
on the supporting electronics. Specifically, the OAWG transmitter architecture in Fig. 1
utilizes efficient spectral multiplexing based on a specialized gapless spectral multiplexer to
create a continuous, arbitrary spectrum over its operating bandwidth. In this fashion, the
modulation format and symbol rate can be flexibly changed in software, and are not restricted
by the transmitter architecture. Thus, an OAWG transmitter is able to generate high-bandwidth single carrier signals in various formats and spectral efficiencies (e.g., QPSK, 8PSK, etc.) or the complete multi-carrier spectrum of CoWDM or optical OFDM signals with independent control of the subcarrier frequency spacing and subcarrier baud rates. In contrast, previously described CoWDM [4,5] and optical OFDM [6–8] transmitter structures require that the subcarrier baud rate is equal to the subcarrier frequency spacing to ensure orthogonality between subcarriers.

Figure 1(a) shows the transmitter architecture which consists of three main components: a
spectral demultiplexer, an array of four-quadrature modulators (FQMs), and a special spectral
multiplexer. First, an optical frequency comb (OFC) is spectrally demultiplexed with narrow
passbands placing each comb line on a separate spatial location. Next, parallel modulations
from an array of FQMs simultaneously modulate the comb lines to create the spectral slices.
FQMs, such as in-phase/quadrature-phase (I/Q) modulators, are preferred over simpler polar
(amplitude/phase) modulators due to the FQM’s ability to generate any spectral slice in a
bandwidth limited manner [18]. Lastly, the spectral slices are coherently combined using a
spectral multiplexer with purposely broadened and overlapping passbands. The result is a broadband gapless spectrum which constitutes a modulated data waveform. This technique is bandwidth scalable without increasing the demand on the supporting electronics due to the parallel nature of the spectral slice modulations.

Since an OAWG transmitter depends on the coherent combination of many spectral slices to ultimately form a broadband output waveform, it is necessary to begin with a set of coherent comb lines. In this case, each comb line has the same temporal phase. As a result, the linewidth (i.e. phase noise) is the same for all comb lines and therefore the same for each spectral slice. Consequently, the aggregate waveform after spectral slice combination has the same temporal phase noise as the incident comb lines, and is subject to the same laser linewidth based performance degradations (i.e., packet length) and potential DSP based corrections as other coherent communications systems [19].

Figure 2 shows the OAWG transmitter DSP algorithm for determining the necessary $I(t)$ (in-phase) and $Q(t)$ (quadrature-phase) modulations for each FQM [18]. According to Fig. 2(a), a target waveform, $a(t)$, is converted to a complex spectrum, $A(f)$, via a discrete Fourier transform (DFT). At this point, a set of $n$ spectral slice filters, $S_n(f)$, divides the total spectrum into overlapping spectral slices. There are many possible spectral slice filter designs, but a requirement is that the sum of all spectral slices results in the original target waveform spectrum. Next in Fig. 2(b), each spectral slice is preemphasized for the spectral multiplexer transmission function, $H_n(f)$, and an inverse discrete Fourier transform (IDFT) yields the temporal $I(t)$ and $Q(t)$ modulations that drive the modulators to create the spectral slices [see Fig. 1(a)].

![Fig. 2. DSP algorithm for the case of two spectral slices. (a) Separating target signal into overlapping spectral slices, (b) adding preemphasis for spectral multiplexer transmission, and determining temporal I/Q modulations for each FQM.](image_url)

The effective number of bits (ENOB) of a digital to analog convertor (DAC) used to generate $I(t)$ and $Q(t)$ modulations will impact waveform fidelity. DAC ENOB is directly related to the achievable optical signal-to-noise ratio (OSNR), which results in an increased DAC ENOB requirement for modulation formats with an increased number of bits per symbol. Appropriate selection of spectral slice bandwidth and modulation format can ensure successful waveform generation for a given DAC ENOB. Note that the DAC ENOB required in a particular scenario is constant over time, and is independent of the packet length. There is also a tradeoff between the spectral slice bandwidth, which is limited by the speed of the supporting electronics, and the number of spectral slices, which is limited by the optics [18]. The 10 GHz spectral slice spacing indicated in Fig. 1 is a good compromise and falls within
the frequency range that optical spectral multiplexers, optical modulators, and electronic DACs overlap. Further investigation on this topic will be the subject of a future publication.

Since an OAWG transmitter functions by generating the spectrum of a target waveform, the target waveform needs to be fully specified for a certain time duration, which introduces an equivalent latency. This transmitter latency can be reduced by first temporally slicing a target waveform and performing spectral slicing [Fig. 2(a)] on each time slice [18]. In this case the minimum latency is determined by the time duration of the time slices. Similar to OFDM, real-time implementations of an OAWG transmitter will require performing a discrete Fourier transform. For the case of an OAWG transmitter, the size of the Fourier transform can be limited by implementing time slices. However, there is a tradeoff between latency and waveform fidelity that becomes significant as the latency approaches the OFC period [18]. In contrast, for OFDM the Fourier transform size is fixed by the number of subcarriers.

3. Two slice, coherent optical transmitter demonstrations

In order for an OAWG transmitter to continuously produce high-fidelity waveforms, coherence between the spectral slices must be maintained. This is challenging when using fiber pigtailed components such as those used in the following proof-of-concept demonstrations since the separate fiber paths introduce random phase fluctuations between the various spectral slices. Possible methods of path length stabilization include implementing an integrated version of an OAWG transmitter, by using a common mode arrangement (i.e., bulk-optics shaper), or active path length stabilization [20]. However, even without any type of active path length stabilization, the spectral slice phases are typically correct (high fidelity) for 8% of the measurements. Eventual monolithic [21] or hybrid integration of the OAWG transmitter will eliminate the phase fluctuations between spectral slices and provide continuous high-fidelity waveforms. This section presents examples of single carrier waveform generation in DPSK, QPSK, and 8PSK modulation formats using a 2 × 10 GHz OAWG transmitter.

Two slice experimental arrangement

Figure 3 shows the experimental arrangement for a two slice, 20 GHz bandwidth proof-of-concept demonstration of an OAWG transmitter. Figure 3(a) depicts the OAWG transmitter which started with a two line, 10 GHz OFC generator (OFCG) based on a single-frequency laser (100-kHz linewidth) and a high extinction-ratio Mach-Zehnder modulator biased at its null point and driven by a 5 GHz sinusoid (i.e., double-sideband suppressed carrier modulation). The two lines were isolated by a custom spectral demultiplexer consisting of a...
10-GHz × 100-channel arrayed-waveguide grating with customizable passband shapes enabled by phase modulators on the array arms. As Fig. 3(b) indicates, the demultiplexer had narrow isolating passbands with −22 dB of adjacent channel crosstalk. The FQMs were implemented using two I/Q modulators (12-GHz bandwidth) and driven by an electronic arbitrary waveform generator (eAWG) with 5.5 GHz of analog bandwidth (12 GSa/s). Each spectral slice was configured to have 10.5 GHz of optical bandwidth and a 0.5-GHz spectral slice overlap. The spectral multiplexer that combined the two spectral slices was also a 10-GHz × 100-channel arrayed-waveguide grating, but had broad overlapping passbands with −17 dB of adjacent channel crosstalk and a −6 dB adjacent channel crossing point [see Fig. 3(c)].

Since the eAWG only had two independent outputs, a time-interleaving scheme was used to provide the four independent I and Q signals needed by the two I/Q modulators. By putting a 100 ns delay after one I/Q modulator and creating two sets of 100-ns long I/Q signals that are temporally concatenated, the two spectral slices were independently generated. In this manner, a 100-ns long optical waveform was created within the 216.67-ns total I/Q signal period. A 100-ns delay before the other I/Q modulator improved the coherence between slices by balancing the path length of the two channels.

Figure 3(d) shows the digital coherent receiver [22] based on a 90° optical hybrid, balanced photodetection, and a two-channel 50-GSa/s digitizer with 16 GHz of electrical bandwidth and 4 μs record lengths. The digital coherent receiver setup was capable of measurements with > 30 dB SNR. The single-frequency laser from the transmitter was also used as the reference (R) at the receiver. The offline DSP enabled reconstruction of the received waveform from the detected I(t) and Q(t) signals, and included a phase estimation technique to minimize phase drift between signal and reference laser [23]. Additionally, software based eye and constellation diagrams were generated, and bit error rate analysis was performed by appropriately sampling the reconstructed waveform.

**High spectral efficiency QPSK and DPSK waveforms**

![Fig. 4. 20 GBd DPSK waveform with a spectral efficiency of 1 b/s/Hz (a) spectrum (b) eye diagram, and (c) constellation diagram. 20 GBd QPSK waveform with a spectral efficiency of 2 b/s/Hz (d) spectrum, (e) eye diagrams, and (f) constellation diagram.](image)

As in any transmission system, a balance must be found between spectral efficiency and system distortion that enables the highest data throughput over a particular bandwidth within a predetermined error tolerance. A significant factor in determining the optimal spectral
efficiency is the type of Nyquist modulation filter used to band-limit the resultant waveform [24]. These experiments use a raised cosine modulation filter that has a $\beta$ parameter which is adjusted to vary the filter shape from a rectangle filter ($\beta = 0$) to a raised cosine shape ($\beta = 1$) or any value in-between [25]. For a fixed bandwidth, setting $\beta = 0$ will maximize data throughput at the cost of increased ripples in the time domain, while setting $\beta = 1$ will reduce the spectral efficiency by half and minimize ripples in the time domain [12].

Figure 4 shows two slice waveform generation results using a raised cosine function with $\beta = 0$ (rectangle function) as a modulation filter for increased spectral efficiency at the cost of increased time domain ripple. Figures 4(a)–4(c) show the measured spectrum, eye diagram and constellation diagram for a 34,000-bit DPSK waveform with a symbol rate of 20 Gbd and a spectral efficiency of 1 b/s/Hz while Figs. 4(d)–4(f) show the measured spectrum, eye diagrams and constellation diagram for a 68,000-bit QPSK waveform with a symbol rate of 20 Gbd and a spectral efficiency of 2 b/s/Hz. The high spectral efficiency modulation filter used results in a rectangle shaped spectrum [Figs. 4(a) and 4(d)] in which the center frequency (0 GHz) represents the center frequency of the OFC. Figures 4(b) and 4(e) show an open DPSK eye and nearly open QPSK eye diagrams, while the constellation diagrams in Figs. 4(c) and 4(f) are well separated indicating the potential for error free detection. These waveforms show that an OAWG transmitter is capable of creating waveforms over its complete operating bandwidth with a high spectral efficiency $\beta = 0$ modulation filter.

8PSK waveforms

Figure 5 presents the measured spectrum and constellation diagram for a 51000-bit, 8PSK waveform with a symbol rate of 10 Gbd and spectral efficiency of 1.5 b/s/Hz ($\beta = 1$). As higher order modulation formats are attempted, the generated waveform’s fidelity becomes more critical and also more apparent. The maximum spectral efficiency of an OAWG transmitter is determined by the achievable fidelity of the generated waveform. Figure 5(b) shows that the measured constellation points are not completely isolated which is a result of small errors between the target and measured waveforms. Increasing the fidelity of the generated waveform requires more precise OAWG transmitter calibration techniques (i.e., removal of frequency dependent component responses, etc.).

Flexible bandwidth allocation

Figure 6 shows two slice results for a 14.492 Gbd (69 ps symbol period), 1 b/s/Hz 24,633-bit DPSK waveform, created with a $\beta = 0$ modulation filter, that intentionally uses only part of the available bandwidth of the OAWG transmitter. This data rate was chosen to demonstrate that an OAWG transmitter can generate output waveforms at any data rate within its bandwidth constraints, and it also emphasizes that the symbol rate need not have any relation to the OFC spacing. Figure 6(a) shows the DPSK waveform’s 20-GHz-wide spectrum while Figs. 6(b) and 6(c) show the corresponding eye diagram and constellation diagram, respectively. The open eye, well-separated constellation points, and error-free performance
prove that the fidelity of the generated waveform is maintained even though the modulation parameters are very different from those used in Figs. 4(a)–4(c).

Fig. 6. 14.492 Gsymbols/s DPSK waveform (0.069 ns symbol period) with a spectral efficiency of 1 b/s/Hz (a) spectrum, (b) eye diagram, and (c) constellation diagram.

Figure 7 highlights the ability of the OAWG transmitter to generate signals that occupy any fraction of, or location within, its operational bandwidth (i.e., sum of the spectral slices) with only a change in software. Figures 7(a)–7(c) show the measured spectrum, eye diagram and constellation diagram for a 17,000-bit, 10-GBd DPSK waveform with a spectral efficiency of 1 b/s/Hz when the waveform’s spectrum is centered (i.e., evenly split between the two spectral slices). There is an elliptical shape to the constellation points [Fig. 7(c)] since the temporal amplitude of the high spectral efficiency waveform is more sensitive to slight random phase variations between the two spectral slices. Figures 7(d)–7(f) show the same data when the waveform’s spectrum is offset by 5 GHz (i.e., generated predominantly by a single spectral slice). In this case, the constellation points are more circular since the contributions from the second spectral slice are minimal.

Fig. 7. 10 GBd centered DPSK with a spectral efficiency of 1 b/s/Hz (a) spectrum, (b) eye diagram, and (c) constellation diagram. 10 GBd spectrally shifted DPSK with a spectral efficiency of 1 b/s/Hz (d) spectrum, (e) eye diagrams, and (f) constellation diagram.

Figures 4–7 demonstrate many capabilities of an OAWG transmitter, some of which are enabling factors for its use as a flexible bandwidth transmitter [11,17]. For example, an OAWG transmitter can dynamically allocate the amount of bandwidth (and spectral efficiency) and vary the spectral location of a particular data channel to any amount within its operating range. Additionally, its modulation format independence enables an OAWG transmitter to adjust the spectral efficiency of a data channel as a function of link quality to ensure that the transmission stays within a specified BER in the event of link quality...
degradation. These factors result in increased spectral utilization while efficiently meeting user demand.

**Bit-error-rate performance**

![Figure 8](image.png)

Figure 8 shows the performance of 10-GBd DPSK and QPSK signals generated using a modulation filter with $\beta = 1$. Figures 8(a)–8(c) show the 17,000-bit DPSK waveform’s measured spectrum, eye diagram, and constellation diagram where the spectral efficiency is 0.5 b/s/Hz, and Figs. 8(d)–8(f) show the same types of data for the 34,000-bit QPSK waveform where the spectral efficiency is 1 b/s/Hz. Figure 8(g) shows the measured BER performance for both the DPSK and QPSK waveforms. The BER is based on multiple consecutive measurements for a total of 102,000 bits at each power level. The DPSK waveform has a 5-dB power penalty and the QPSK waveform has a 6-dB power penalty when compared to theoretical values for their respective modulation formats. Due to the number of bits tested at each power level, a BER $< 2 \times 10^{-4}$ indicates less than 20 errors detected. When comparing the generated waveform to the target waveform, it is apparent that the power...
penalties are errors in the generated waveform. Further improvements in the OAWG transmitter calibration techniques (i.e., removal of frequency dependent component responses, etc.) will improve the BER performance.

4. Three slice, coherent optical transmitter demonstrations

This section describes an experiment that extends the two slice OAWG transmitter to three slices to demonstrate the general bandwidth scalability of the spectral slice dynamic-OAWG technique. Further extension of the number of spectral slices will eventually enable the generation of 1-THz bandwidth waveforms. However, as mentioned previously, a useful implementation requires a constant phase relationship between the many tens of spectral slices necessary to create such a large bandwidth. Although theoretically possible with bulk-optic or actively-stabilized arrangements, the most practical implementation would use a fully integrated device [21]. In particular, this section presents single carrier QPSK waveform generation using a 3 × 10 GHz OAWG transmitter.

Figure 9 shows the experimental arrangement for the three slice OAWG transmitter. Conceptually, it is an extension of the two slice experiments from Section 3 but with two significant differences: the OFCG, and the spectral demultiplexer that separates the comb lines. Here, the 10-GHz multiline OFCG was based on strong modulation of a single-frequency laser (100-kHz linewidth) in both amplitude and phase to create seven comb lines within −10 dB [26], which were bandpass filtered to three lines within ± 0.5 dB of each other. In Fig. 9(a), the spectral demultiplexer of Fig. 3 was replaced with a spectral deinterleaver which directs ‘even’ comb lines to one output and ‘odd’ comb lines to the other output. Figure 9(b) shows that the deinterleaver had better than −30 dB adjacent channel crosstalk. A time interleaving scheme similar to that in Section 3 enabled the two independent eAWG outputs to drive the two I/Q modulators and create three independent spectral slices. One I/Q modulator (even) created a single spectral slice and the other (odd) created two spectral slices. Here, the waveform durations were 4 ns, and the relative delays were 5 ns and 10 ns. Figure 9(c) illustrates the timing of the temporal interleaving. At this point, combining the three spectral slices using the same spectral multiplexer as that shown in Fig. 3(c), yielded the desired output waveform, S. The undesired comb lines were filtered out by the spectral multiplexer.

Figure 9(d) shows the equivalent-time heterodyne measurement technique used to characterize the output waveforms. The reference signal, R, was generated by frequency

![Fig. 9. Three slice experimental arrangement. (a) OAWG transmitter for three slice signal generation with measured (b) spectral de-interleaver. Spectral multiplexer transmission is the same as Fig. 3(c). (c) Time interleaving scheme for aligning the three spectral slices. (d) Coherent receiver for three spectral slice signal measurement. IQM: I/Q modulator. AOM: Acousto-optic modulator. OFCG: Optical frequency comb generator.](image-url)
shifting the single-frequency laser by 35 MHz using an acousto-optic modulator (AOM). The output of a 2 × 2 coupler used to mix the signal and reference was sent to a balanced photodetector and difference signal was digitized by a 50 GSa/s real-time oscilloscope. Offline, the complex optical signal spectrum was recovered from the measured heterodyne signal. This heterodyne measurement enabled full-field detection over 32 GHz of bandwidth with a 15 Hz update rate (limited by computer processing time). In this case, each measurement is the average of 240 waveforms.

Figure 10 presents the three slice results for a 144-bit, 30-GHz QPSK waveform at 18 Gb/s and a spectral efficiency of 1.2 b/s/Hz generated using a modulation filter with $\beta = 0.6$. Figure 10(a) shows that the measured QPSK waveform’s phase is in close agreement with the target values (dark gray). Figure 10(b) displays the measured spectrum, which is a close match to its target, while Fig. 10(c) shows the eye diagrams and Fig. 10(d) the constellation diagram of the averaged waveform. Both indicate the potential for error-free performance.

![Figure 10](image)

Fig. 10. 18 Gb/s, 144-bit, 4 ns, 30 GHz QPSK signal with a spectral efficiency of 1.2 b/s/Hz. (a) Temporal waveform (light gray lines indicate QPSK phase levels), (b) spectrum, (c) eye diagrams, and (d) constellation diagram. Target values are in dark gray. Measurements are averaged over 240 waveforms.

5. Conclusions

This paper presented a next generation modulation format independent optical transmitter based on the parallel synthesis of multiple spectral slices. The bandwidth scalable nature of this transmitter was verified through experimental generation of modulated data waveforms created from two and three independent 10 GHz bandwidth spectral slices. Experiments also demonstrated that an OAWG transmitter can satisfy the requirements for a flexible bandwidth transmitter by changing the bandwidth and spectral location of a transmission with merely a software change. As the integrated device technology continues to mature, a THz bandwidth OAWG transmitter chip will become a reality [21].

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