Optical Spectrally Sliced Transmitter for High Fidelity and Bandwidth Scalable Waveform Generation

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Abstract—This paper presents a single-carrier optical coherent transmitter that synthesizes high-fidelity waveforms from N spectral slices with the state-of-the-art electrical drivers. The synthesis technique overcomes the electronic speed bottlenecks and produces an optical waveform bandwidth that is N times the electrical bandwidths. Using two 32 GHz slices, we synthesized and transmitted a 60-GbD polarization-division multiplexed, quadrature phase-shift keying (PDM-QPSK) waveform over 4480 km with a Q²-factor of 8.71 dB. To demonstrate high-fidelity waveform synthesis, we generated a 60-GbD PDM 16-QAM and observed a 2.5-dB implementation penalty at BER of 1 × 10⁻². To address scalability, we also developed the phase mismatch compensation algorithm for the transmitter that uses photonic integrated circuits.

Index Terms—(060.1660) Coherent communications, (320.5540) pulse shaping.

I. INTRODUCTION

HERE has been significant interest in high-fidelity and large bandwidth waveform generation, which helps meet the demands for capacity increase and flexible network operation in today’s optical fiber network. Increasing the waveform bandwidth simplifies the network engineering because it reduces the number of transmitters and receivers, and high-fidelity waveforms increase the capacity because they support more bits per symbol. In addition, a variety of applications, such as biological nanotechnology, imaging systems and radar systems, also require single-carrier large bandwidth waveforms [1], [2]. Many approaches, such as all-electronic time-division multiplexing [3], dual-carrier with electronic multiplexing [4], multicarrier transmitters [5], and silica waveguide based spectrum synthesis circuit [6], can offer large bandwidth optical waveforms. However, none of these can control an entire continuous spectrum that can scale to large bandwidths with infinite word-lengths, and high-fidelity.

An ideal transmitter should be able to generate any modulation format across very large chunks of spectrum (i.e., 100-GHz to the entire C-band) with high-fidelity. Full control of the entire spectrum would enable the ultimate flexibility in network operation. Typical optical spectrum management is mainly limited by the rigid spectral grid of the multiplexers [7]. For instance, software-defined-networking could benefit from the ability to dynamically change the spectral efficiency, baud-rate or the number of subcarriers. Furthermore, the linear impairments of the optical channels could be pre-compensated and inter-channel nonlinear impairments can be mitigated from the transmitter side [8]–[10]. All these techniques benefit from full control of large bandwidths.

Unfortunately, the fidelity of standard high-baudrate signal degrades as the bandwidth is increased because the electronic and opto-electronic components, such as digital-to-analog converters (DAC), electronic amplifiers and I/Q modulators, perform poorly above 50 GHz. For example, Raybon et al., [4], [11] reported a single carrier, high baudrate transmitter capable of producing a 214-GbD QPSK waveform, but it could not create a 16-QAM due to the lack of a multi-level electrical driver. On the other hand, multicarrier transmitters such as orthogonal frequency-division multiplexing (OFDM) achieve much higher total data rates by combining multiple lower data rate subcarriers [5]. However, OFDM transmitters suffer from inter-channel nonlinear impairments due to the closely packed carriers [12].

We present a spectrally-sliced transmitter that combines phase-coherent parallel spectral slices to generate large bandwidth waveforms with high-fidelity. The phase coherent slices are generated by modulating the lines of a coherent optical frequency comb to produce slices. The bandwidth can scale because we use low-loss optics to combine the slices and the waveform fidelity does not decrease as we add slices, because the fidelity is set by the lower speed electronics. Later,
waveform generation. The bandwidth of the waveform is equal to the product of the number of slices and the slice spacing, and the length of the waveforms are set by the length of the electronic modulation waveforms. The input to the transmitter is a coherent optical frequency comb. Each combline of a coherent optical frequency comb is separated using wavelength demultiplexers (e.g., arrayed-waveguide gratings (AWG) or WSS with a high extinction ratio). Each spectral slice is produced through the electro-optic modulation of an individual combline using the state-of-the-art electrical components covering a moderate bandwidths (e.g., 20 GHz). These slices are then coherently combined without gaps using a wavelength multiplexer (or power combiner) with a gapless spectral transmission. The combined spectral slices synthesize the desired continuous waveform. Not to be confused with multi-carrier modulator, the transmitter uses many narrowband slices to synthesize a much broader waveform that is not restricted by the comb spacing. For instance, waveforms could be a high-speed single carrier signal of any modulation format, or even multi-carrier OFDM or WDM that has completely different channel spacing than the input comb. Thus, the slice spacing can be adjusted to either optimize the waveform fidelity by using narrow bandwidth slices that use electrical components with higher fidelity, or maximize the waveform bandwidth by using the widest bandwidth slices that can be produced by the electro-optic components. With I/Q modulation, the optical bandwidth is twice the electronic bandwidth. Since the waveform fidelity is set by the electronics, the bandwidth can always be extended without sacrificing fidelity.

Manipulating each spectral slice allows us to reduce the bandwidth of RF electronics, which could help design a cost-effective transmitter and extend the scalability. Moreover, we could implement flexible bandwidth operation without a fixed frequency grid because the waveform shaping algorithm is not constrained to the comb spacing, which increases the flexible bandwidth management efficiency.

III. ALGORITHM TO DETERMINE MODULATION SIGNALS ON THE COMB LINES

The modulation signals on each slice are chosen so that the combined waveform matches the target waveform and are determined using inverse Fourier synthesis. First, the target waveform, $e_T(t)$, is defined in the temporal domain using all the bandwidth of the spectrally-sliced transmitter. Next, we determine the spectrum of the waveform, $S_T(f)$, using a Fourier transform. $S_T(f)$ is separated into many slices using spectral slice filters. We used raised-cosine filters with roll-off factor of 0.01 with both the bandwidth and spacing equal to the comb spacing. When the roll-off factor is 0, the raised-cosine filters are square and the resulting slices will not have any overlap. When the roll-off factor is greater than 0, the adjacent slices overlap spectrally, but when summed together they produce the proper waveform without any distortion. The slices are then pre-emphasized to correct for the frequency response of the front-end optics (e.g., multiplexers) and electronics (e.g., electronic drivers). These corrections include the phase and
amplitude response of the optical multiplexers, modulators, DACs, and electronic amplifiers. The complex driving signals to each modulator are the inverse Fourier transform of the slice centered on the combline. For I/Q modulators, we extract the real and imaginary parts of the complex driving signals, and apply to the I/Q modulator through DACs [16], [17].

IV. ITERATIVE PROCEDURE FOR WAVEFORM SHAPING

The waveform shaping procedure optimizes the modulation signals for each spectral slice to synthesize the target combined waveform with the highest available fidelity through iterations. Experimentally iterations easily remove non-trivial transmitter distortions (i.e., nonlinearities) and can not be implemented for real-time processing. A real-time system would need a different technique such as a look-up table to compensate non-trivial transmitter distortions. Fig. 2 shows the flowchart of the waveform shaping algorithm, which includes two parts: 1) providing modulation to the isolated optical comblines, which broadens the combline into a spectral slice (as discussed in Section III), and 2) iterative optimization to reduce the waveform error waveforms [18]. In a continuous system, iterative optimization is not possible, however for this study it allows us to determine the fidelity of the transmitter after optimization.

There are many ways to measure the fidelity of waveforms including: the effective number of bits (ENOB), the signal-to-noise ratio (SNR), error vector magnitude (EVM) and normalized energy error. Here, we use the EVM which is defined as the square root of the ratio of the power of the error waveform (i.e., error vector) to the power of the target waveform. The original definition of EVM is a figure of merit to determine the waveform quality of shaped constellations, but it also works for continuous waveforms [17]. The error vector can be calculated either in the time-domain or the frequency-domain since for continuous waveforms [17]. The error vector can be calculated either in the time-domain or the frequency-domain since the power of the error vector is the same in both domains. For instance, in the spectral domain EVM equals the square root of the ratio between the intensity of the error waveform (i.e., \[|S_M(f)|^2 - |S_T(f)|^2\]) to the intensity of the target waveform (i.e., \[|S_T(f)|^2\]) [15]. In the time-domain it is computed as the square root of the ratio between the intensity of the error waveform (i.e., \[|e_M(t)|^2 - |e_T(t)|^2\]) and the intensity of the target waveform (i.e., \[|e_T(t)|^2\]). To eliminate measurement noise from the waveform shaping, we average 160 measured waveforms together before computing the EVM [19]. In this paper, a high fidelity waveform has EVM below 4% which enables theoretical BER values from distortions alone of \(<1 \times 10^{-20}\) and \(2.95 \times 10^{-17}\) for QPSK and 16 QAM.

The setup used to measure and generate waveforms is described in Fig. 4, and will be discussed in Section V. For optimization, we remove the polarization multiplexer, operate at \(\sim 35\) dB OSNR, and measure \(6 \times 10^6\) samples at 120 GS/s on the oscilloscope. The pattern length of the 60-Gb/s 16 QAM and QPSK are 32 768. We retrieved the averaged waveform using four offline digital signal processing (DSP) procedures that include: 1) oscilloscope front-end corrections such as gain, timing skew, 2) 2× oversampling, 3) phase error correction, and 4) waveform averaging of 160 waveforms to suppress the measurement noise. The waveform stored in the DAC at each iteration is defined as \(e_i(t)\), and the measured waveform is \(e_{m_i}(t)\), where \(i\) is the iteration number.

Each slice is optimized independently with the others turned off. The EVM presented is the average of the two slices separately. The starting waveforms, \(e_0(t)\), contains only corrections for the frequency roll-off, skew, of the DAC. \(e_{m0}(t)\) typically has EVM of \(<30\%\) which is not high fidelity (e.g., the calculated BER at EVM of 30% of 60-Gb/s QPSK is \(4.29 \times 10^{-4}\). The residual waveform errors are likely from the non-ideal response of the RF amplifier, nonlinear frequency response of the I/Q modulator, and inter-symbol crosstalk and other nonlinearities in the DAC. These degradation mechanisms are difficult to remove with simple pre-emphasis, therefore, we use an iterative procedure that subtracts the waveform error from the DAC waveform until the \(e_{m_i}(t)\) equals \(e_i(t)\). The waveform update equation is \(e_{i+1}(t) = e_i(t) - 0.1 \times (e_i(t) - e_{m_i}(t))\). We stop iterations when the EVM is smaller than 4%, which corresponds to a theoretical BER value of \(2.9 \times 10^{-17}\), for a 16-QAM signal. Fig. 3(a) presents the EVM values of \(e_{m_i}(t)\), which shows the reduction of the EVM by 7 after nine iterations. However, the measured EVM for the combined waveform is slightly larger (5%–7%), because the multiplexer has some finite crosstalk. Fig. 3(b) compares a section of the 60-Gb/s QPSK target waveform and measured averaged waveform after nine iterations in the time domain and frequency domain. Fig. 3(c) illustrates the evolution of the waveform error (complex field) from the first iteration to the ninth iteration is reduced by seven times. Fig. 3(d) shows the constellation of the averaged waveform (160 averaged waveforms) after the ninth iteration for 60-Gb/s QPSK and 60-Gb/s 16-QAM.

Iterative optimization corrects for the non-trivial transmitter distortions so we can investigate the best performance of the spectrally-sliced transmitter. The optimized EVM values of the QPSK waveform and the 16-QAM waveform are \(\sim 5\%\) and \(\sim 7.2\%\), which correspond to BER values of \(<1 \times 10^{-20}\) and \(\sim 1.37 \times 10^{-8}\), respectively.

V. EXPERIMENTS

Fig. 4 shows the experimental arrangement of the spectrally sliced transmitter that uses two parallel spectral slices. Two
comblines were generated by modulating an external cavity laser (100 kHz linewidth) at 1546.12 nm using a Mach–Zehnder modulator. An RF synthesizer provided a 33.28125 GHz tone. After amplification, the optical power of each combine is ~15 dBm. In this experiment, we used a Santec WSS as the frequency demultiplexer, which provided larger than 35 dB isolation between adjacent spectral slices. We used a 2 x 2 power combiner instead of a multiplexer (e.g., AWGs) to combine the two slices, which induces 3-dB loss. Transmitters with more than two slices should use WSS or AWGs for scalability. The Santec WSS is based on liquid crystal on silicon technology which supports 12.5-GHz flexible grid operation. On the output ports of the WSS, we measured >35 dB extinction ratio between each optical comblines. Each output combine was separately modulated by an I/Q modulator. A state-of-the-art DAC provided the I/Q modulators driving signals and contains four channels with a maximum sampling rate of 65 GS/s, resolution of 8-bits, and ENOB of 6.5. We used polarization controllers before each I/Q modulator to align the polarization state to the I/Q modulators polarization axes. PCs after each I/Q modulator aligned the polarization states of the two slices. These PCs were optimized by maximizing the output power after the polarization beam splitter. The signal was then amplified by a polarization maintaining erbium doped fiber amplifier (PM-EDFA), and sent to a polarization division multiplexer (Pol Mux) with delay difference of a 22 920 symbols (i.e., 382 ns) to emulate a PDM signals. In consequence, the transmitter produces PDM waveforms with 60-Gb/s data rate.

The power levels and OSNRs of the transmitter at each step is: (1) the output power of the transmitter is ~15.2 dBm with 35 dB OSNR (0.1 nm bandwidth resolution); (2) the loss of the WSS is ~11 dB with attenuation; (3) the loss of the modulator is ~16 dB after QPSK waveform modulation; (4) the excess loss of the PDM emulator is ~1 dB; (5) the max power level input to noise loading EDFA is ~14 dBm which produces max OSNR after it of 35 dB. The power budget shows that the output of the transmitter could achieve sufficient OSNR for the long-haul transmission (4480 km) with a power margin of ~5 dB for the 60-Gb/s QPSK.

The right hand side of Fig. 4 shows the noise loading setup that contains a programmable optical variable attenuator and an EDFA. Increasing the attenuation loads additional amplified spontaneous emission noise to the signal. An optical spectrum analyzer with 0.1 nm resolution monitors the OSNR values. The receiver is a polarization diversified digital coherent receiver that contains an
local oscillator (LO, 100 kHz linewidth) laser, a polarization diversity 90° optical hybrid, the balanced photodetectors and a four channel real-time oscilloscope with 120 GS/s sampling rate (2 × the baud rate).

We calculated the BERs of the received data using offline DSP. First, the DSP corrects for front end errors including timing skew, hybrid phase error, and frequency roll-off of the balanced photodetectors and oscilloscope. Next, we applied a 2 × 2 MIMO equalizer that contains 67 T/2-spaced (T = 1/60 ns) tap finite impulse response (FIR) filter adapted by a constant modulus algorithm [20] for the QPSK waveform, and by a multi-level modulus algorithm [21] for the 16-QAM waveform. The number of the taps that we used in the FIR filter was smaller than the delay values in the Pol Mux. After the equalizer converges, we used the Viterbi–Viterbi algorithm [22] for LO frequency offset and phase recovery. We then use a hard-decision threshold to convert the constellation point to a bit sequence and count bit errors from 950 000 symbols.

Fig. 5 presents the b2b BER performance of the 60-GBd QPSK and 16-QAM waveforms. Since the transmitter uses fiber pig-tailed components to generate and combine the spectral slices, each measurement has a random phase misalignment between the two spectral slices. As a result, we took ten data sets at each OSNR with 2 million samples of each data set to investigate the statistics of the BER performance. Because the phase error is a unitary distortion (i.e., lossless), it is not expected to degrade the BER if the equalizer converges. Fig. 5(a) shows the 60-GBd QPSK waveform with best (red), average (green) and worst (purple) BER out of ten measured data sets at each OSNR. At a BER of 1 × 10^{-3}, the OSNR variation was <1 dB between the best and worst BER values, which indicates that the

![Fig. 5](image-url)
measurements was repeatable and stable as also reported by [14]. At high OSNRs (OSNR > 30 dB), 90% of the measured data sets were error free. Fig. 5(b) shows the statistical analysis of the measured data sets at OSNR value 16–24 dB. The maximum variation of the Q\(^2\)-factor is < 2 dB at 22-dB OSNR. We observed 1.5-dB OSNR implementation penalty at BER of 1 × 10\(^{-3}\) for the 60-Gb/s QPSK waveform at the best BER measurement condition. The spectral efficiency of the PDM QPSK waveform is 3.59 bit/s/Hz due to the chosen roll-off factor of 0.01. Fig. 6(a) and (b) shows the constellation after offline DSP for 60-Gb/s PDM QPSK waveform at 19-dB and 34-dB OSNR, separately.

Next, we investigated high-fidelity waveform generation of a 60-Gb/s 16-QAM waveform. Fig 5(c) shows the best BER performance out of ten data sets. The 16-QAM waveform had only ∼2.5 dB OSNR implementation penalty at BER of 1 × 10\(^{-2}\) with 7.18 bit/s/Hz spectral efficiency. Fig. 6(c) and (d) shows the constellation after offline DSP for 60-Gb/s PDM 16-QAM waveform at 19-dB and 34-dB OSNR, separately. The result clearly indicates that we can use the transmitter to generate a high-quality waveform with an advanced modulation format. The second experiment evaluates the transmission of the 60-Gb/s QPSK waveform using a recirculating loop. Fig. 7 shows the experimental arrangement of the recirculating loop, which contains 4 × 80 km (320 km per loop) standard single mode fiber and EDFA’s. Every four spans, a WSS was used for spectral shaping (gain flattening) followed by an additional EDFA to compensate for loop losses. The electro-optic switches that control the loop and signal were triggered by two RF waveform generators, respectively. We used a 3-dB 2 × 2 coupler to load the signal in/out of the loop. The output of the loop was sent to the coherent receiver with the LO for further signal processing.

We optimized the launch power of the transmitter at the beginning of the recirculating loop by looking for a balance between the OSNR and the fiber nonlinearity. The total launch power was 3 dBm. In the DSP, we removed the chromatic dispersion from the long-haul (320 km to 4480 km) fiber transmission. Fig. 8 shows the single-channel transmission performance with different amount of spans for the 60-Gb/s PDM QPSK waveform (blue dot curve). After 4480 km transmission, the BER was 3.2 × 10\(^{-3}\), which is below the HD-FEC limit (3.8 × 10\(^{-3}\), [23]) and the Q\(^2\)-factor, which is defined as:

\[
Q^2 = 20 \log_{10}(\sqrt{2/\text{erfc}^{-1}(2 \times \text{BER})})
\]

was 8.71 dB.

VI. SCALING BANDWIDTHS AND FIDELITY

Spectrally-sliced transmitters use low-loss wavelength multiplexing optics to scale to large bandwidths and high-fidelity lower speed electronics to produce continuous waveforms. The main source of waveform degradation is the phase-mismatch between slices when the waveforms are combined. Fig. 9 shows a simulation example of a waveform in the spectral and time domain with and without slice phase errors. Spectrally-sliced receivers can correct the phase-mismatch without errors in the offline DSP [14]. Spectrally-sliced transmitters must ensure that the slices are combined with the correct phases otherwise the waveform in the fiber is incorrect. In telecommunication applications, adaptive equalizers can correct the phase error because the distortion is unitary.

Photonic integration of the spectrally-sliced transmitter enables control and stabilization of the phases between spectral slices. Fig. 9(a) shows the integrated device which contains AWG demultiplexers, I/Q modulators, and an array of phase shifters. The phase shifter is an optical heater that uses optical-thermal effect to change the effective refractive index of the material, which is mainly used to compensate the constant phase offset between spectral slices across one spectral slice channel. A 30-GHz channel is only 0.015% of the wavelength and therefore is achromatic across a slice. Random phase mismatch between slices severely distorts the waveforms. Phase errors are built into the comb source and can be introduced from path length mismatches in the PIC. Fig. 9(b) illustrates the simulated phase variations of all of the combines. Fig. 9(c)
shows a simulation of a waveform (super-Gaussian waveform) with and without random phase-mismatch in time domain. Using the phase shifters, we could find phase variations of all the combines. Since the PIC can be thermally stabilized, the phases only need to be corrected once or drift very slowly (<Hz). Fig. 9(d) shows the simulated output waveform without and with the phase-mismatch correction in frequency domain. This type of photonic integration can scale the spectrally-sliced transmitter to large bandwidths.

VII. CONCLUSION

We have demonstrated a single carrier based spectrally sliced transmitter that generated 60-GBaud QPSK and 16-QAM waveforms using two spectral slices. We discussed the waveform shaping algorithm and an iterated optimization procedure to investigate the ultimate fidelity of the transmitter. The 60-GBaud QPSK waveform showed high fidelity (EVM ~ 5%) and propagated through an optical loop that only uses EDFAs for amplification. After 4480 km transmission, the measured BER of 3.2 × 10^{-3} was below HD FEC limit (BCH(1 020 988) super FEC code, 7% overhead) with a Q^2-factor of 8.71 dB. We also proved that the transmitter can generate advanced modulation format such as 16-QAM with 2.5 dB implantation penalty at BER value of 1 × 10^{-2}. Future work includes developing advanced PIC devices to implement the transmitter structure with better stability and investigating real-time DSP algorithms for continuous waveform generation.

REFERENCES


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Dr. Xie has authored and coauthored more than 200 journal papers and conference publications, two book chapters and one book in print. He is an associate editor of Journal of Lightwave Technology, and has served as chairs, TPC chairs or TPC members in many conferences.

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