Bandwidth Scalable and High Fidelity Spectrally-Sliced Transmitter

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Abstract: We demonstrate a high-fidelity transmitter based on the synthesis of multiple spectral slices and transmit a 60-GBd PDM-QPSK waveform over 4480 km with a Q^2-factor of 8.71-dB using two slices.

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1. Introduction

Many technology choices for high capacity optical channels are being investigated where trade-offs between performance, spectral efficiency, flexibility, complexity and routing are being considered. Multicarrier solutions such as orthogonal frequency-division multiplexing (OFDM) [1] achieve increases in total capacity using multiple lower symbol rate subcarriers, but are accompanied by complex guard band requirements and suffer from lower interchannel nonlinear performance [2]. High symbol-rate single-carrier signals operating for 50 to 100 Gbd can have better tolerance to interchannel nonlinear impairments, and can be easier to route than multiplexed channels such as in OFDM systems [3]. However, the bandwidth limitations of electrical components currently presents a bottleneck to achieving high data-rate single carrier signals [4]. Spectrally-sliced transmitters [5, 6] can produce wideband waveforms that look like they were created by a single modulator, by coherently combining multiple spectral-slices. Each spectral slice is created by modulating one line of an optical frequency comb and requires only a fraction of the waveforms’ total bandwidth, which enables generation of high bandwidth signals using lower-bandwidth equipment (e.g., E/O modulation, signal processing, etc.). The spectral slice technique provides tradeoffs for: 1) total waveform bandwidth, by operating the electronics at their limits and using wide slice bandwidths or 2) waveform fidelity, by using narrower slices and operating the electronics at lower bandwidths where they produce higher-fidelity waveforms. A waveform-shaping algorithm and associated digital signal processing (DSP) determine the modulation for each line and enables high-fidelity synthesis through the inclusion of pre-compensation for impairments due to the electronics and photonics (e.g., frequency-dependent loss, dispersion, etc.).

In this paper, we shaped and transmitted a 60-GBd polarization division multiplexing (PDM) quadrature phase-shift keying (QPSK) waveform using two spectral slices over 4480 km with a Q^2-factor of 8.71-dB.

2. Experimental Arrangement

![Experimental arrangement showing the (a) transmitter and the back-to-back measurement setup, and (b) the transmission setup.](image-url)
Fig. 1 shows the experimental arrangement. A spectrally-sliced transmitter consists of three components: 1) an optical frequency comb that provides phase-locked carriers, 2) an array of full-field modulators (I/Q) to generate the spectral slices, and 3) a wavelength multiplexer (or power combiner) to combine the slices. In this experiment, the comb generator had two lines spaced at a 33.28125 GHz and they were produced by modulating an external cavity laser (ECL) at 1546.12 nm with a Mach-Zehnder modulator (MZM). A flex-grid wavelength-selective switch (WSS) demultiplexed the two comb lines and directed them to different modulators. Each comb line was modulated by a separate I/Q modulator using the signals from a 4-channel, 60 GS/s digital-to-analog converter (DAC) to produce each spectral slice, independently. The DAC’s effective number of bits (ENOB) was ~6.5. A 2×1 power combiner summed the spectral slices to generate a Nyquist shaped 60-GBd QPSK waveform with a pattern length of 32,768 symbols. A polarization multiplexer stage with a decorrelation of 22,920 symbols (382-ns) emulated polarization multiplexing. The waveform was sent either directly to the coherent receiver with noise loading for back-to-back bit-error-rate (BER) measurements or to the loop for transmission experiments.

Fig. 1(a) also shows the back-to-back BER experimental arrangement. A digital variable optical attenuator and an erbium-doped fiber amplifier (EDFA) was used to vary the optical signal-to-noise ratio (OSNR). We used an optical spectrum analyzer (OSA) after the EDFA to monitor the OSNR values with a 0.1-nm resolution bandwidth. Both the transmitted signal and local oscillator (LO) signal entered a polarization diversified coherent receiver which included a real-time oscilloscope with a 45-GHz analog bandwidth and a 120-GS/s sampling rate. The linewidths of both the transmitter ECL and LO ECL were 100 kHz.

Fig. 1(b) shows the recirculating loop for transmission testing which consists of 80-km spans of SSMF and amplification using only EDFAs. A WSS was used for additional gain flattening after the four spans. Electro-optic loop switches and a 3-dB coupler were used to load the loop. The signal was received using the same polarization diversified digital coherent receiver with a separate local oscillator (LO) centered at 1545.986 nm.

3. High Fidelity Waveform Shaping

![Diagram of waveform shaping algorithm](image)

The fidelity of the generated optical waveform was quantified using error vector magnitude (EVM) [7] which represents the normalized field error. EVM is defined as the square root of the ratio between the energy of the error waveform (i.e., \( |S_{\text{err}}(f) - S_T(f)|^2 \)) to the energy of the target waveform (i.e., \( |S_T(f)|^2 \)). Here \( S_{\text{err}}(f) \) and \( S_T(f) \) are defined as the average measured waveform and target waveforms, respectively. After optimizations, the QPSK waveform had an EVM less than 10.11%, which supports QPSK with a theoretical BER of 2.27×10⁻²³.

Fig. 2(a,b) shows a diagram of the waveform shaping algorithm. First, we generate the target waveform such as a Nyquist-shaped QPSK waveform. The target waveform’s spectrum is computed using a discrete Fourier transform (DFT). Then two separate raised-cosine filters spaced by 33.28125 GHz with 0.01 roll-off factors are used to slice the spectrum into two. Each slice is then down-converted to baseband (DC) and the slices are inverse discrete Fourier transformed (IDFT). The real and imaginary components are the two target modulations and these are pre-emphasized for any filtering effects of the DAC, modulator driver, and modulator. The 4-channel DAC applies these pre-emphasized modulations to each I/Q modulator. To further optimize the waveforms, we use feedback to compensate for nonlinear frontend impairments such as inter-symbol interference on the DAC, nonlinearity of the IQ modulator, etc. After several iterations (up to 10), we achieve a high-fidelity waveform with an EVM <10.11%. If the waveform has an EVM < 11.2%, theoretically it supports 16-QAM with a BER below 1×10⁻³.

We chose a slice spacing of 33.2815 GHz because the DACs can still produce a high-fidelity waveform without requiring excessive pre-emphasis. The waveform shaping algorithm is not limited to a particular type of waveform and it will work for more advanced modulation formats (i.e., 16-QAM or 64-QAM) [8].
4. Transmission Experiment and BER Performance

Fig. 3 shows results from back-to-back and loop transmission experiments. We apply offline digital signal processing (DSP) for BER analyses. The measured waveform is processed by a finite impulse response (FIR) filter with 67 T/2-spaced taps (T = 1/60 ns), adapted by the constant modulus algorithm (CMA)[8]. After CMA equalization, we use a Viterbi-Viterbi algorithm [8] for frequency and phase recovery and the BER is calculated from 950,000 bits.

Fig. 3(a) shows the back-to-back measurement results for the shaped 60-GBaud PDM QPSK. The 1.5-dB OSNR implementation penalty may be due to waveform shaping errors. Fig. 3(b) shows the BER performance for different transmission distances for the shaped 60-GBd PDM QPSK signal. The total launched power was 3 dBm (experimentally optimized as a balance between OSNR and nonlinearity). The blue curve shows single-channel transmission for the shaped 60-GBd PDM QPSK signal. The result shows that after 4480 km, we can achieve a BER of $3.2 \times 10^{-3}$, which is less than HD-FEC limit ($3.8 \times 10^{-3}$) [9]. Fig. 3(c) shows the measured QPSK waveform with a center frequency of 193.9 THz and a spectral width of 66 GHz. The result shows a spectral efficiency of 3.2 bit/s/Hz. Fig. 3(d) shows the constellations at high OSNR (35 dB) and low OSNR (18 dB) of the PDM-QPSK signal after offline DSP phase recovery.

5. Summary

We have demonstrated a single-carrier 60-GBd PDM-QPSK waveform synthesized using two spectral slices. The recombined waveform shows high fidelity (EVM < 10.11%) and was transmitted up to 4480 km with a BER of $3.2 \times 10^{-3}$ $(Q$-factor: 8.71 dB). This approach can produce wide-bandwidth single carrier waveforms without increasing the electrical bandwidth. It is scalable and has potential applications in broadband waveform generation, high-baud rate and high fidelity systems.

6. References


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