Demonstration of High-Fidelity Dynamic Optical Arbitrary Waveform Generation

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Abstract: Interfacing two I/Q modulators and a passband shaped spectral demultiplexer allows the coherent combination of two arbitrary modulated spectral lines to generate dynamic optical waveforms with 20 GHz bandwidth and 6 ns record lengths.

The generation of arbitrary optical waveforms with both terahertz bandwidth and long record lengths (> 1 ns) is an ongoing technical challenge [1-4]. Such waveforms have new and exciting applications in telecommunications and optical signal processing [1, 3]. Techniques such static optical arbitrary waveform generation (OAWG) in which the phase and intensity of each line of an optical frequency comb (OFC) are controlled using a Fourier domain waveformshaper (see Fig. 1), can produce broadband waveforms [1, 5]. However, since the waveform shaper is essentially a highly reconfigurable filter, the output waveform is repetitive (i.e., shaped OFC) with a maximum duration equal to the input OFC’s period. It has been suggested that applying rapidly updating, or ‘dynamic’, modulations to each comb line can break the periodicity of the OFC, thus generating continuous and broadband waveforms [1-3]. In those studies, spectral multiplexer filtering is identified as a severe limiting factor for waveform fidelity and update rate. This summary demonstrates a dynamic-OAWG technique that overcomes those limitations by using a spectral domain algorithm to calculate the comb line modulations and a waveform shaper design that incorporates both quadrature modulation and a specially designed spectral multiplexer. The technique provides for long record length, high-fidelity waveforms in a bandwidth scalable fashion. Here, we show a demonstration using a two line, 10 GHz OFC and fiber-pigtailed components that verify the dynamic-OAWG concept and algorithm.

Fig. 1(a) shows the dynamic-OAWG concept and its experimental implementation. First, a spectral demultiplexer with low adjacent channel crosstalk places each comb line of the input OFC on a separate output channel. Next, independent quadrature modulations broaden each comb line to produce spectral slices. Then, a spectral multiplexer with overlapping passbands coherently combines the spectral slices to produce the desired continuous waveform spectrum, \( D(f) \). A close match between \( D(f) \) and the target spectrum, \( A(f) \), ensures accurate output temporal waveform, \( d(t) \), generation. The key to the waveform shaper is its use of in-phase and quadrature-phase (I/Q) modulators, which are much more electrical-bandwidth efficient than amplitude and phase modulators for arbitrary modulation, and an arrayed-waveguide grating (AWG) multiplexer with purposely broadened passbands so that the output waveform has a gapless spectrum. Finally, a set of comb line modulations required to produce the desired output waveform are calculated using an algorithm that includes pre-emphasis for the spectral multiplexer.

Fig. 1(b,c) illustrates how the algorithm determines a set of comb line modulations, including pre-emphasis for the multiplexer transfer function, \( H_n(f) \) where \( n \) is the comb line index, that produce the desired output waveform. Following Fig. 1(b), the complex target spectrum, \( A(f) \), of the long (many OFC periods) target waveform, \( a(t) \), is computed using the discrete Fourier transform (DFT). \( A(f) \) is divided into spectral slices using a set of spectral slice filters centered on each comb line (\( S_n \) are a mathematical construct). A requirement for the spectral slice filters is...
that the summation of all the spectral slices must equal the target spectrum. Fig. 1(c) shows that to generate spectral modulations compatible with the multiplexer, each spectral slice is pre-emphasized for the multiplexer transfer function, \(H_m(f)\). Then, the inverse DFT (IDFT) of each spectral slice produces the necessary temporal modulations. The real and imaginary components are the driving signals for the \(I\) and \(Q\) channels for each modulator. Additionally, these \(I\) and \(Q\) modulations must include calibration for the electrical response of the system.

In this experiment, a two line, 10 GHz comb source is created with a single-frequency laser and a high extinction-ratio Mach-Zehnder modulator biased at its null point, and driven by a 5 GHz sine wave (i.e., double-sideband, suppressed-carrier modulation). A delay interferometer (50 ps) is used as the spectral demultiplexer (adjacent passband crosstalk is less than \(-25\) dB). Each comb line is independently modulated using a \(I/Q\) modulators with 12 GHz of modulation bandwidth. An electronic arbitrary waveform generator (eAWG) with two independent 12 GS/s outputs produces the temporal \(I/Q\) signals for the modulators. A time-interleaving technique is used to generate the four independent signals necessary to drive the two \(I/Q\) modulators for a limited time (approximately 8 ns). The eAWG outputs a periodic waveform repeating every 16.66 ns (i.e., 60 MHz repetition rate). The spectral multiplexer is a 10 GHz silica AWG with a quadratic phase profile across the array arms to purposely broaden the AWG passbands. This results in an adjacent channel crossing point of \(-6\) dB and \(-17\) dB of adjacent passband crosstalk (measured transmission shown in Fig. 1(a)).

Fig. 2 shows the measurement results with a 6 ns target waveform consisting of a transform-limited pulse, a pulse with cubic spectral phase, and a pulse with quadratic spectral phase; a 20th-order super-Gaussian spectral amplitude filter defines the spectral envelope yielding a total waveform bandwidth of 20 GHz. An optical heterodyne measurement technique facilitated simultaneous measurement of each spectral slice (measurement points \(A\) and \(B\) in Fig. 1(a)) and the output waveform (measurement point \(C\) in Fig. 1(a)). The fiber-pigtailed components are susceptible to environmental fluctuations that cause a slowly varying phase relationship between the two spectral slices. Therefore, only measurements that have the correct relative phase are shown. Fig. 2(a) shows the measured temporal modulations, and Fig. 2(b) shows the spectrum, at points \(A\) and \(B\). A slight overlap of the spectral slices facilitates the generation of a gapless spectrum, and mitigates time domain ringing of the modulations. In this case, a 1 GHz overlap of the modulated lines is used, which corresponds to 11 GHz wide spectral slice filters. The approximately 20 dB of adjacent comb line rejection could be improved using a better comb line demultiplexer. Fig. 2(c,d) shows that the measured waveform is a high-fidelity reproduction of the target in both the spectral and temporal domains. The energy in the error waveform (i.e., the difference between the signal and target) is 2 %. This level of accuracy was achieved using a thorough calibration of the waveform shaper components and did not require any iterative algorithms or feedback. More importantly, the waveform shows no resemblance to the input OFC; the waveform’s spectrum is continuous without dips and the temporal domain waveform has no periodicity related to the OFC.

In conclusion, we have successfully demonstrated high-fidelity dynamic-OAWG to generate complex optical waveforms that are 6 ns (60 OFC periods) in duration. The technique is scalable in bandwidth and capable of continuous waveform generation. Future demonstrations of dynamic-OAWG that use an integrated-optic platform will ensure stability between the spectral slices while also providing an easy way to incorporate large modulator arrays and scale the number of spectral slices [4].

References

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