Multichannel Radio-Frequency Arbitrary Waveform Generation Based on Multiwavelength Comb Switching and 2-D Line-by-Line Pulse Shaping

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***Abstract*— We demonstrate a multichannel time-multiplexed radio-frequency arbitrary waveform generator. The system combines a switching scheme of multiwavelength optical frequency combs with a novel 2-D line-by-line pulse shaper featuring broad bandwidth operation over large temporal windows. Switching times within a clock period of 200 ps among the four channels is successfully achieved. With finer pulse shaper resolution, the number of channels can be scaled up without increasing the number of switching components.**

***Index Terms*— Electrooptic modulators, microwave generation, microwave photonics, optical pulse shaping.**

I. Introduction

ARBITRARY radio-frequency waveform generators (RF-AWGs) are valuable testing and diagnostic tools in communication systems, defense electronics, and computing. In the quest towards ultra-broad bandwidth operation, there has been substantial research effort in photonically enabled RF-AWGs, since the achievable bandwidth becomes higher than with state-of-the-art digital-to-analog converters [1-6]. Among the different reported solutions, those involving pulse shapers provide programmable arbitrary RF waveforms with superior time-bandwidth product (TBWP) [2-5].

However, conventional pulse shaping geometries, e.g., direct space-to-time [2] or Fourier [3-5], as well as arrayed waveguide routers in planar lightwave circuits [6], offer a very limited update rate of the synthesized waveform (~kHz at best), mainly given by the reconfiguration speed of the active shaping element. Because it seems unlikely that these technologies will evolve in the near future to provide the nanosecond-class refresh times needed by the most demanding applications, there has been a push to explore different switching mechanisms that effectively enable an ultra-rapid update of the synthesized RF waveforms. Recent solutions include, e.g., switching between two optical frequency combs centered at different wavelengths shaped with a single shaper [7]; switching between waveforms synthesized from two spectral processors [8]; switching laser arrays with predefined power and wavelength separation [9]; or shifting the central frequency of one comb shaped with a single pulse shaper that interleaves two masks with twice finer resolution [10]. Although the results achieved by these techniques are promising, scaling the schemes to more than two waveforms becomes a challenging task. The difficulty comes from either the added complexity in the optical setups and/or the need for sophisticated electrical sequences to control the switching.

We recently reported a concept for multiwavelength optoelectronic-comb switching that only requires a single optoelectronic component for all the wavelengths. When combined with line-by-line pulse shaping, the preliminary results in [11] show that the architecture allows for arbitrary switching between predefined waveforms, with a switching time down to the single waveform period. This enables construction of broadband RF waveforms that may be non-repeating with infinite record length. Here we provide further experimental results and demonstrate programmable line-by-line pulse shaping of four wavelength-selected 5-GHz repetition rate combs. The optical pulse shaping is carried out in a novel 2-D configuration [12] incorporating a programmable 2-D spatial light modulator (SLM) display [13]. This solution ensures simultaneous broad-bandwidth operation and fine resolution. The overall system leads to a 4-channel time-multiplexed RF-AWG with an ultra-broad RF-bandwidth content just limited by the photodiode response time.

II. Principle of Operation

The principle of operation for our multichannel RF-AWG is illustrated in Fig. 1 (a). Several continuous-wave (CW) lasers centered at different wavelengths are externally modulated by an array of electro-optic modulators, generating an optical frequency comb around each CW source. The multiwavelength frequency comb is sent to a dispersive medium to

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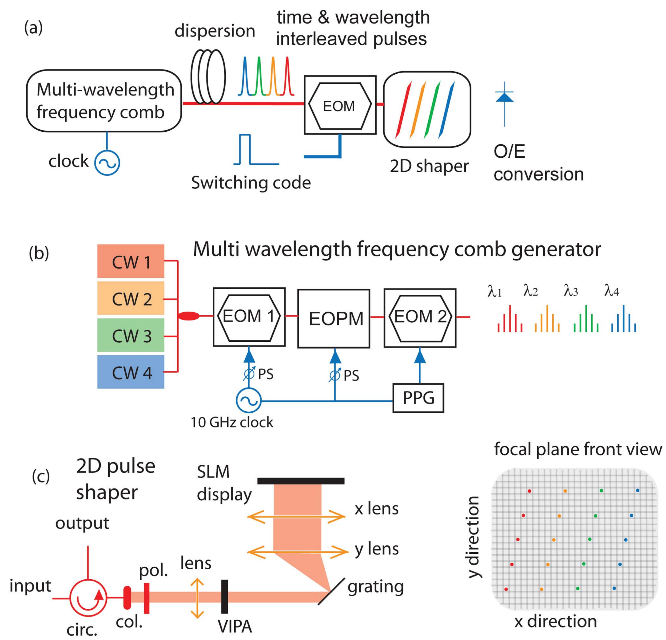

Fig. 1. (a) Schematic representation of the proposed system. (b) Multiwavelength frequency comb generator setup. (c) Layout of the 2-D pulse shaper. Every single line from a comb source can be independently controlled by an addressable element with the SLM display. EOM: electro-optic modulator. CW: continuous-wave laser. EOPM: electro-optic phase modulator. PS: phase shifter. PPG: pulse pattern generator. circ: circulator. col: collimator. pol: polarizer. VIPA: virtually imaged phase array. SLM: spatial light modulator.

compensate for the inherent chirp, leading to a compressed multiwavelength pulse train and introducing a time delay between consecutive pulses [14]. The N different wavelengths will be interleaved inside a fundamental comb period T if $D\Delta\lambda = T/N$, where D is the dispersion amount and $\Delta\lambda$ the comb wavelength separation. This parallel-to-series conversion allows for selecting a particular wavelength inside a period provided a sufficiently fast switching mechanism is available. Unlike [7-10], this scheme only requires a single opto-electronic modulator to switch the wavelengths. The maximum number of waveforms that can be multiplexed is $N_{max} = T/\sigma$, where σ is the optical switching gate duration. After switching, the signal is sent to a pulse shaper with a spectral resolution, δf, equal to or better than the frequency comb repetition rate, i.e., $\delta f = 1/T$. Thus, given a gate duration, a pulse shaper with finer resolution helps to increase the number of multiplexed channels while maintaining a single comb generator setup, a single switching element, and a single pulse shaper. In addition to the programmed waveform, the pulse shaper introduces a linear spectral phase to the final mask to correct the relative delay of the switched waveform inside a period. Finally, the sequence of optical waveforms is detected with a high-speed photodiode (PD), leading to a programmable sequence of predefined arbitrary RF waveforms. The transition time between programmed waveforms is given by the clock source.

III. System Description

A. Multiwavelength Comb Switching

The optical frequency comb generator is depicted in Fig. 1(b). Four tunable DBR lasers are coupled and modulated by an intensity (EOM1) and phase modulator (EOPM) arranged in tandem, driven by a clock source at 10 GHz. When the intensity modulator EOM1 is properly biased, this system provides an optical frequency comb with flat envelope and a frequency spacing given by the clock source. We introduce another electro-optic modulator (EOM2), acting as pulse picker, driven by the sequence "10" produced by a 10 Gb/s pulse pattern generator (PPG), with the aim to reduce by twice the repetition rate of the master comb source without altering the spectral envelope. As shown in Fig. 2(a), we synthesize four optical frequency combs each with a fundamental period of $T = 200$ ps (5 GHz spacing) and 40 lines at -10dB bandwidth. Broader combs could be achieved by cascading more phase modulators. More lines at lower repetition rates can be introduced by programming a longer sequence on EOM2.

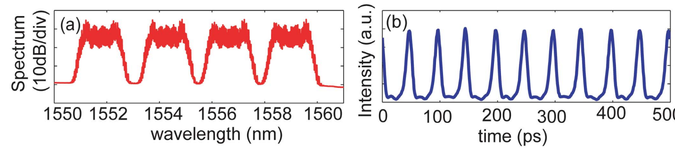

Fig. 2. (a) Multiwavelength 5-GHz frequency comb spectra. (b) Intensity profile of time- and wavelength-interleaved pulse trains.

As a dispersive element, we use 1.2km of single-mode-fiber. The wavelength- and time-interleaved compressed-pulse train is shown in Fig. 2(b). In order to achieve the 50 ps time spacing, we set a frequency comb separation of $\Delta\lambda \sim 2.6$ nm. There are no appreciable differences in the compressed pulses at different wavelengths. Afterwards, the desired wavelength is gated by another EOM driven by an electrical pattern sequence synthesized with an electrical AWG working at 20 GS/s and triggered with the 10GHz clock source. The measured optical gate has a full width at half maximum duration of $\sigma \sim 54$ ps, leading to a maximum number of multiplexed channels $N_{max} \sim 4$. At this bandwidth and wavelength separation, up to 15 channels could be multiplexed if the spectral resolution in the pulse shaper was reduced accordingly to $\sim$1.25 GHz. It is worth noting that even better resolutions have been reported in 1-D VIPA shapers. At full bandwidth, the third-order-dispersion effects in the compression stage could be easily compensated for by nonlinearly spacing the CW wavelengths.

B. 2-D Line-by-Line Pulse Shaping and RF-AWG

For this application, a pulse shaper featuring broad bandwidth operation and fine spectral resolution is required. We adopt a Fourier transform pulse shaper in a novel 2-D configuration that permits us to exploit the whole 2-D range offered by SLMs based on liquid crystal on silicon displays [13]. Our shaper uses a VIPA with 200 GHz free spectral range (FSR) as a spectral disperser in the y-dimension. It is the enormous angular dispersion introduced by this device which allows us to achieve fine spectral resolution. Then, a grating with a pitch of 940 lines/mm breaks the degeneracy imposed by the FSR of the VIPA and disperses the wavelengths that are separated by one FSR to different spatial locations within the horizontal direction. Two different cylindrical lenses, one for the VIPA

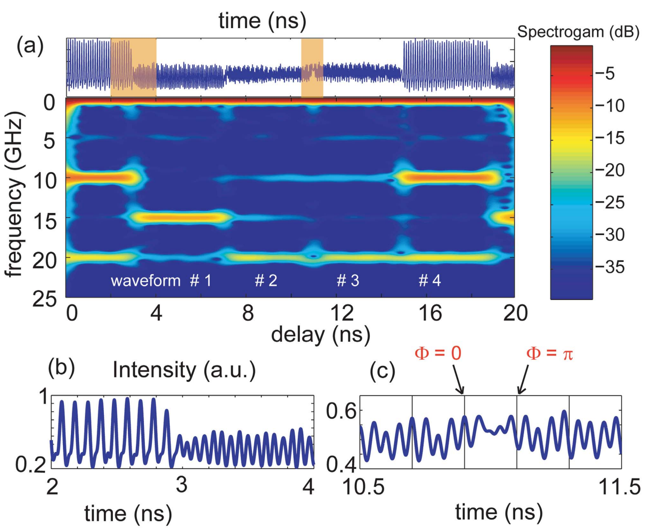

Fig. 3. (a) Singe-shot intensity sequence measured at 50 GS/s showing the four synthesized waveforms, each lasting for 4 ns, and corresponding spectrogram computed using a 400-ps Gaussian gate. (b) and (c) Zoom of the shadow regions in (a) where the transients between waveforms 4 to 1 and 2 to 3 occur, respectively.

and another for the grating, are used to focus the angularly dispersed components into the Fourier plane, where the SLM display (HOLOEye HEO1080P) is located. Overall, the device in this configuration has >1000 addressable elements in the C-band with ~3 GHz resolution. Afterwards, the synthesized and switched optical waveforms are sent to a 20GHz PD to generate the multichannel RF-AWG. The signals are monitored with a real-time sampling oscilloscope with 20 GHz bandwidth and 50GS/s.

IV. Experimental Results

As an example, we have programmed spectral-phase masks based on the temporal Talbot effect [15] to show the capabilities of the system in switching between high-frequency and phase-modulated RF signals. Waveform #1 is synthesized to provide a 15 GHz repetition rate pulse train (3× multiplication); #2 a 20 GHz pulse train (4×); #3 is a π-phase shifted replica of #2; and #4 is a 10 GHz repetition rate pulse train (2×). The sequence programmed corresponds to twenty 200 ps periods, or 4 ns, per waveform. A single-shot sequence acquired with the oscilloscope is displayed in Fig. 3 (a).

The transition between waveforms #4 and #1 is displayed in Fig. 3(b), showing a switch time corresponding to ~200ps. The computed spectrogram for the whole sequence shows that such extremely rapid change is also achieved for the other RF waveforms. As expected from the repetition-rate multiplication factor, each waveform has an RF bandwidth content centered around multiple integers of the synthesized repetition-rate frequency. The roll-off at high frequencies can be explained by the limited bandwidth of the PD and scope. Finally, the π-phase jump between waveforms #2 and #3 is better visualized with the aid of the vertical bars in Fig. 3(c), which are separated 200 ps apart (a frequency comb period). This shows the system is also capable of introducing programmable phase shifts on high-frequency signals.

V. Conclusion

Based on optoelectronic frequency comb technology, we have demonstrated a four-channel time-multiplexed RF-AWG. Each programmed waveform has a bandwidth just limited by the PD and can be switched within a clock period by a user-defined electrical pattern. The scalability of the system is ensured by the parallel-to-serial conversion in multiwavelength pulse compression and the use of a programmable 2-D pulse shaper featuring broad bandwidth operation and fine resolution.

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