Programmable Line-by-Line Pulse Shaping with a Microresonator-Based Spectral Shaper

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***Abstract*—We describe a method for programming microresonator-based integrated photonic spectral pulse shapers and implement it experimentally on a 6-channel silicon photonic device with narrow linewidth resonators to compress lines from a 3 GHz electro-optic comb.**

***Index Terms*—integrated photonics, programmable pulse shaper**

I. Introduction

Optical pulse shapers that can modify the spectral phase and amplitude of an optical signal play an essential role in various applications like optical arbitrary waveform generation [1] and spectral quantum information processing [2]. Photonic integrated circuits (PICs) provide excellent platforms for pulse shaping, possessing the advantage of compact size and potential for finer spectral resolution compared to commercial counterparts utilizing bulk optics. On-chip shapers have been realized using arrayed waveguide gratings (AWG) [3], [4], but have drawbacks like fixed channel spacing, large footprint, and challenges achieving fine spectral resolution on the order of GHz. Microring resonators functioning as spectral filters could alleviate these problems [5], enabling a fine spectral resolution limited by the resonance linewidth and center frequency tunability via the thermo-optic (TO) effect. However, the large-scale control of these shapers becomes complicated by thermal crosstalk effects, and a truly programmable solution has not yet been shown. In this work, we present a method for programming such shapers onto arbitrary frequency grids and with arbitrary phases. We employ a simultaneous multi-heterodyne (MH) and dual-comb spectroscopy (DCS) measurement to control the channel position and phase, respectively. The method is used to compress lines from a 3 GHz electro-optic (EO) comb into transform-limited pulses in the time domain.

II. Experiment

Our pulse shaper PIC (Fig. 1(a)) is built on the silicon-on-insulator (SOI) platform fabricated by AIM Photonics. The shaper has a single input waveguide coupled to an array of microresonators. Each resonator downloads a unique slice of the input spectrum and routes it to a TO phase shifter before being uploaded to a common output waveguide via an identical resonator. The resonators have a linewidth of 1.1GHz, drop-port loss of 2.5dB, and free spectral range (FSR) of 110GHz.

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When combined to form a shaper channel, the linewidth is ~ 900MHz with ~ 6 dB of insertion loss (as indicated in Fig. 1(b)). Though each resonator has the same design, the as-fabricated resonances are scattered due to imperfections in fabrication. The spectral filtering function of the shaper requires resonances of each filter within a channel to be well-aligned in order to efficiently modulate the spectral phase, unless some amplitude modulation is desired.

We implement a MH measurement technique with electronic feedback to align resonators within a shaper channel. A portion of the spectrum from a mode-locked frequency comb is sent through loopbacks on both the download and upload sides of the shaper, as the green arrows in Fig. 1(a) indicate. The strong coupling between the bus waveguides and resonators leads to a significant (~ 10 dB) frequency-dependent extinction as measured from the output of the loopbacks, indicating the resonance frequencies of the resonators. This frequency-dependent response is encoded as amplitude modulation of the lines of the comb. By combining the modulated comb exiting the loopback waveguides with a continuous wave (CW) laser emitting at a fixed wavelength and beating on a high-speed photodetector (PD), the optical response can be downconverted to the radio frequency (RF) range after measurement by an oscilloscope and fast-Fourier transform (FFT). The optical spectrum is revealed as amplitude modulated tones spaced at the repetition rate of the comb (250 MHz). This MH measurement enables multiple optical spectra to be measured at the same time (limited by the number of oscilloscope channels) and supports high rates of spectrum measurement, with each measurement taking on the order of 10milliseconds. By varying the resonator drive currents incrementally and processing the RF spectrum each time, the resonance frequencies of the download and upload resonators within each channel can be tracked and tuned to arbitrary frequency positions (relative to the CW laser). In our experiments, we align shaper channels to a uniformly spaced frequency grid.

To measure the spectral phase applied to each channel, we adopt a DCS method with two EO combs generated using the same pump. The signal comb is driven with a frequency equal to the spacing of the shaper channels (f_{sig}) and the reference comb is driven at a slightly different frequency ($f_{ref} = f_{sig} + \Delta f$). The two oscillators driving the combs are synchronized to each other. Signal comb modes on the

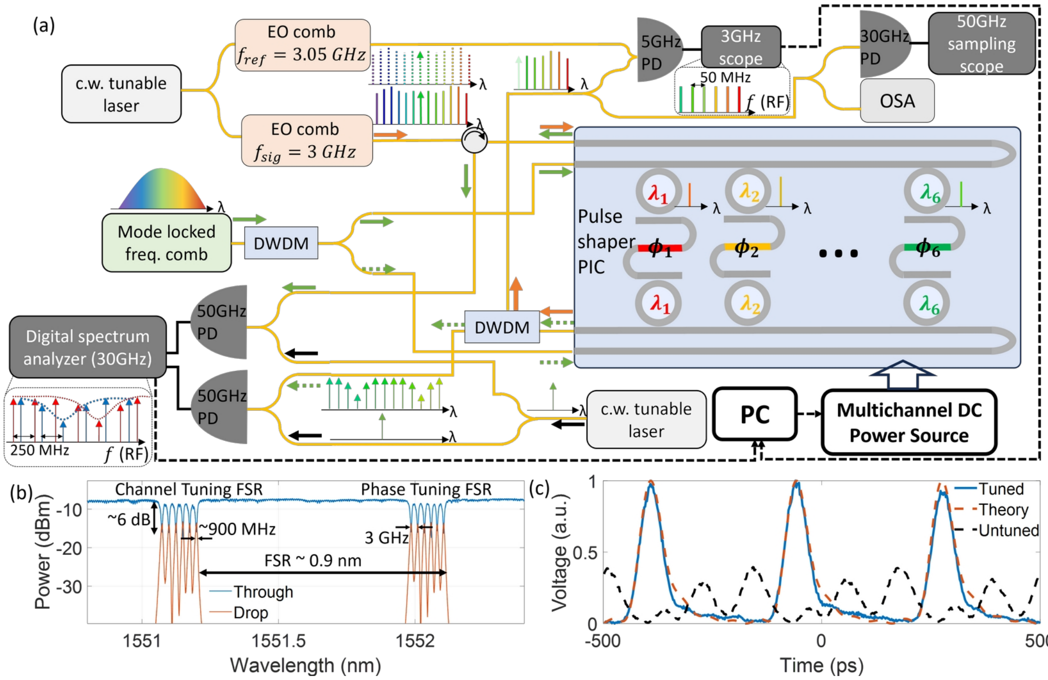

Fig. 1. (a) Illustration of the simplified experiment setup. DWDM: dense wavelength division multiplexer. OSA: optical spectrum analyzer. PC: computer. DC: direct current. (b) Frequency response of the spectral shaper tuned to compress 6 lines of the 3 GHz signal comb, as measured by a swept laser source. (c) Temporal traces measured by 50 GHz sampling scope with the phases untuned (black trace) and tuned to zero (blue trace), compared with the theoretical prediction of a transform-limited pulse as measured through our system (orange trace).

high-wavelength side of the pump are sent through the shaper to accumulate the phase applied by each channel. The signal comb exiting the chip through the drop port is combined with the reference comb and sent to a 5 GHz balanced PD. Heterodyne beats at harmonics of the dual-comb difference frequency (Δf) are generated. The phase difference between the signal and reference comb can be measured by acquiring the generated electronic signal using an oscilloscope and sampling the phase at beat notes frequencies after an FFT.

The MH and DCS methods can be performed simultaneously by using the loopback waveguides bi-directionally and employing DWDM spectral filters, as shown in Fig. 1(a). The MH scheme is run on the *channel tuning* FSR and DCS on the adjacent *phase tuning* FSR shown in Fig. 1(b). A Python-based control routine is implemented using these techniques to program the system to operate on uniformly spaced frequency grids and with arbitrary phases. The routine first acts to tune channels onto the frequency grid by repeatedly performing the MH measurement and updating resonator drive currents. When channels are aligned, the DCS method is used to sample the phase. Phase shifter currents are then updated if necessary. The MH measurement is repeated after each phase update in case thermal crosstalk effects act to detune resonators from the grid. If that occurs, resonator drive currents are updated until all channels are aligned back to the grid, and the phase tuning measurement/update process continues. By repeating in this way, thermal crosstalk effects can be compensated for and the device can be programmed.

As a first demonstration, we run the routine to align shaper channels to a 3 GHz grid and compress six lines from the 3 GHz signal EO comb. The signal comb coming out of the chip is split by a fiber coupler. Half of the light is sent for DCS measurement and the majority of the other half goes to a 30 GHz PD for time-resolved measurement of the waveform with a sampling oscilloscope. To compress the lines from the signal comb, we use the routine to set the phase tuners such that the DCS measured phases are the negative of the reference comb spectral phase, which we measure to be approximately quadratic at $\sim$0.009 rad/GHz^2. The initial temporal waveform, where the phase shifters in each channel are not yet tuned, is shown in Fig. 1(c) (black dashed line). After running our control routine, the waveform is shown in Fig. 1(c) (blue solid line), which agrees well with theory given our system response (orange dashed line). The shaper transmission for the pulsed state as measured from a swept laser is shown in Fig. 1(b). The entire control sequence takes just a few minutes to converge.

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