Arbitrary Waveforms From a Fine-Resolution Microresonator-Based Spectral Shaper

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Abstract: We report a scheme for programming microresonator-based pulse spectral shapers and demonstrate it with a six-channel, sub-GHz linewidth, silicon photonic spectral shaper to generate arbitrary waveforms from optical lines of a 3 GHz electro-optic comb.

Optical pulse shaping is a useful technique involving the manipulation of the relative amplitudes and p
spectral slices from a broadband optical spectrum in order to shape the waveform in the time domain. Ex
research over the past couple decades has resulted in robust shaper systems utilizing bulk free space op
with components like diffraction gratings, lenses, and liquid crystal on silicon spatial light modulators [1]
these setups are well-suited for femtosecond, high repetition rate waveform synthesis, they can be excessively
large and incur a significant penalty in terms of optical loss when assembled to achieve fine spectral reso
(order of GHz) necessary for low repetition rate waveforms. There has been a recent desire for fine spect
lution pulse shaping in, for example, generating picosecond waveforms with a low repetition rate for the
control of electronic transitions within molecular ions or atoms [2, 3], or as the driving source for superco
based waveform synthesizers [4], and in spectral quantum information processing [5]. Photonic integrate
(PICs) offer a low size, weight, and power (SWaP) chip-scale platform for pulse shaping. To this end, the a
waveguide grating (AWG) device has been extensively researched. However, the AWG requires long opti
to be operated at a fine-resolution, resulting in a large footprint (∼ cm× cm) and significant optical loss a
errors, especially for high-index contrast platforms like silicon-on-insulator (SOI) [6]. A comparatively sma
number of integrated shaper designs have implemented microresonator-based spectral dispersers [7, 8]
onators benefit from a small footprint, resonance frequency tunability via the thermo-optic effect, and ar
of fine-resolution filtering [9]. Yet, microresonators are challenging to control. Here, we demonstrate a si
shaper on the SOI platform using fine-resolution microresonator filtering elements. We develop a control
to manage the thermal crosstalk within the system and enable programmability of the shaper. We finally
to synthesize arbitrary waveforms in the time domain using optical lines from a 3 GHz electro-optic (EO)

A concept illustration of our six-channel SOI shaper is shown in Fig. 1(a). Within a single integrated chip,

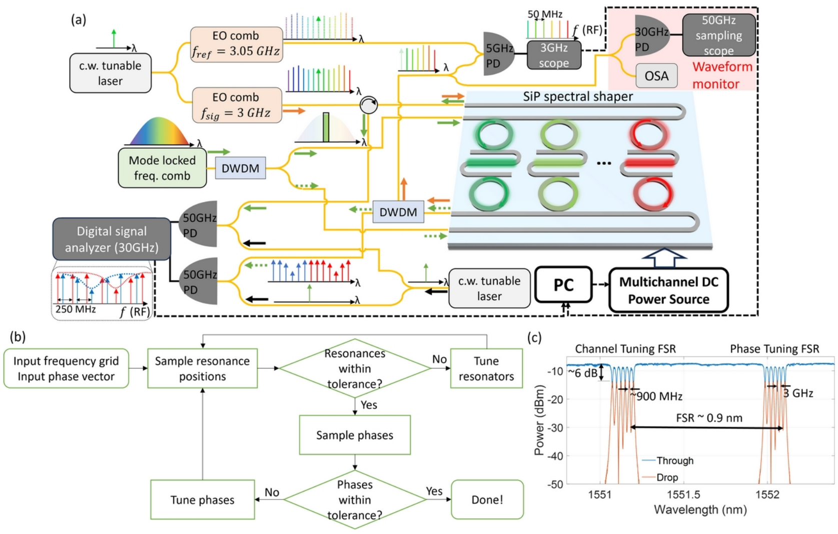

Fig. 1: (a) Diagram of the experimental setup. Yellow lines indicate optical fiber, solid black lines indicate RF cables, and dashed black lines indicate USB cables. PC: Personal Computer, OSA: Optical Spectrum Analyzer, DWDM: Dense Wave-length Division Multiplexer, PD: Photodiode, DC: Direct Current. (b) Flowchart of our shaper control scheme. (c) Tran
sion spectrum of the spectral shaper programmed to compress six lines from a 3 GHz EO comb, as measured from a
laser.

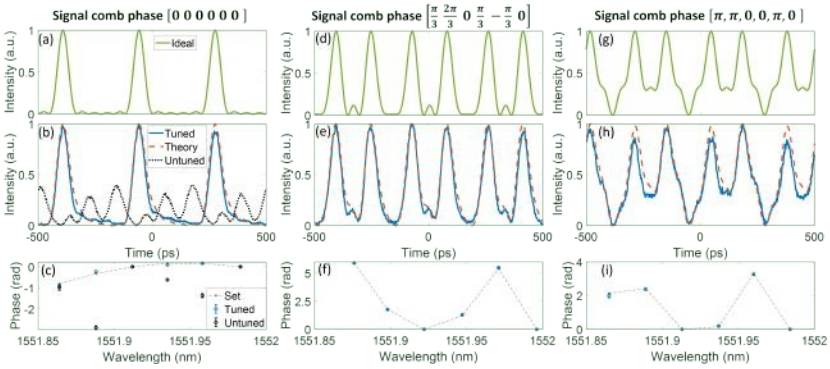

Fig. 2: (a,d,g) Ideal target waveforms in the time domain (green traces) and signal comb spectral phase (top) for the
pressed, Talbot, and forked state, respectively. (b,e,h) Measured waveforms (blue trace) and the ideal waveforms c
with the measurement system impulse response (dashed orange traces) for the compressed, Talbot, and forked sta
tively. An additional waveform is shown in (b) (black dotted trace) with an untuned phase and phase shifters driven
∼ π phase. (c,f,i) Target (gray dashed) and measured (blue scattered with error bars) signal comb spectral phase fo
pressed, Talbot, and forked states, respectively. An additional measurement is shown in (c) (black scattered with er
the untuned phase state, with phase shifters driven to induce ∼ π phase.

channel, a resonator first demultiplexes a spectral slice of an input optical signal and routes it to a therm
phase shifter before being multiplexed back onto a common output waveguide via a second identical res
A six-channel system (twelve resonators and six phase shifters) is built on the SOI platform fabricated by
Photonics. Resonators are designed using multimode waveguides for the benefit of a reduced sidewall ro
and propagation loss. A single shaper channel exhibits a ∼ 900 MHz linewidth, ∼ 115 GHz FSR, and ∼ 6 d
sertion loss. Doped silicon slabs placed adjacent to the waveguides are used for thermo-optic tuning of re
and phase shifters. Loopback waveguides are formed from both the input and output of the shaper. Our t
setup is also shown in Fig. 1(a). Using the loopback waveguide bidirectionally and employing spectral filters,
we simultaneously perform multi-heterodyne spectroscopy (MHS) and dual-comb spectroscopy (DCS) me
ments on two adjacent free spectral ranges (FSRs) of the shaper (Fig. 1(c)) to rapidly (∼ µs) query the re
frequencies of resonators on both sides of the shaper and the phases applied to each line, respectively. B
the power from one of the EO combs used for DCS and routing it to the waveform monitor section in Fig.
can view the temporal profile of six comb lines after propagation through the shaper in real time. A Pytho
routine (block diagram in Fig. 1(b)) is written to actively tune channels onto a particular frequency grid a
distinct phases with feedback from MHS and DCS signals.

As a demonstration of our method, we synthesize three waveforms from six optical lines of the 3 GHz E
The ideal waveforms, the measured and ideally measured (given our measurement system response) wa
and the measured phase on each shaper channel are shown in Fig. 2(a-i). The first demonstration is to co
the six lines from the EO comb to form transform-limited pulses. The MHS scheme is run to align channel
a 3 GHz grid without tuning the phases. However, in our scheme phase shifters are driven at the start to
slightly higher than π phase. The temporal waveform is shown in Fig. 2(b) (black dotted trace) for these s
phases. With phases tuned, the pulses are compressed (blue trace in Fig. 2(b)). The spectral transmissio
system for this state is shown in Fig. 1(e) and the untuned and tuned phases are shown in Fig. 2(c). Next, we
target two additional waveforms: a doubled repetition-rate waveform following the temporal Talbot effec
third waveform we denote the forked state. The various results for these states are shown in Fig. 2(d-i). These
waveforms are highly sensitive to phase deviations and therefore phase tuners needed to be iteratively c
in fine steps to achieve the agreement shown in the figures. This requirement could be eliminated with a
measurement of the reference EO comb phase.

In conclusion, we experimentally demonstrated a scheme for programming microresonator-based spec
shapers. A set of three waveforms are synthesized using a six-channel sub-GHz resolution SOI shaper. Th
shows promise towards realizing fully integrated fine-resolution pulse shaping systems for the next gene
pulse shaping applications.

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