Integrated line-by-line optical pulse shaper for high-fidelity and rapidly reconfigurable RF-filtering

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Abstract: We present a 32 channel indium phosphide integrated pulse shaper with 25 GHz channel spacing, where each channel is equipped with a semiconductor optical amplifier allowing for programmable line-by-line gain control with submicrosecond reconfigurability. We critically test the integrated pulse shaper by using it in comb-based RF-photonic filtering experiments where the precise gain control is leveraged to synthesize high-fidelity RF filters which we reconfigure on a microsecond time scale. Our on-chip pulse shaping demonstration is unmatched in its combination of speed, fidelity, and flexibility, and will likely open new avenues in the field of advanced broadband signal generation and processing.

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OCIS codes: (320.5540) Pulse shaping; (250.5300) Photonic integrated circuits.

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1. Introduction

Over the past few decades optical pulse shaping has become an integral part of numerous photonic systems, impacting applications from optical communications to coherent control of quantum and nonlinear processes [1,2]. Originally the spectral resolving power of pulse shapers was relatively coarse, compared to the mode spacing in frequency combs, which only allowed comb lines to only be controlled in groups. More recently thanks to parallel advancements in both finer-resolution pulse shaping technology and the development of frequency combs with larger repetition rates (10’s of GHz) [3,4] pulse shapers can now work in the ‘line-by-line’ regime, where they can exert complete complex control over the individual lines of a frequency comb [5,6]. This emerging sub-field has been of particular interest for applications in ultrabroadband RF photonics [7–9] such as agile radio frequency (RF) arbitrary waveform generation [10–12] and tunable reconfigurable RF photonic filtering [13–16].

Typically, photonic processing of RF signals involves creating scaled and delayed replicas of RF signals in the optical domain followed by photodetection to generate an RF output. In general, photonic approaches hold an inherent advantage over traditional electronic based schemes in that the RF-signal bandwidth is a much smaller fraction of the optical carrier frequency and is therefore more manageable. Schemes which utilize a multi-wavelength source and a pulse shaper add flexibility by providing a dynamic platform for optimization and reconfiguration of the optical signal and resultant RF impulse response. Further, the quality and achievable complexity of the synthesized RF response can be maximized when the pulse shaping device is capable of precise line-by-line control. However, currently pulse shaping devices capable of providing the desired high fidelity line-by-line control have mostly been demonstrated using architectures that rely on bulk optics, making cost effective implementation outside of the laboratory a challenge. Further, bulk pulse shapers typically utilize liquid crystal spatial-light-modulators (SLMs) which restrict their reconfigurability to the millisecond time scale, too slow for many emerging applications.

Meanwhile, driven primarily by the need for broadband mass transmission of information, the technology behind photonic integrated circuits (PICs) has advanced tremendously over the last decade. Photonic integrated circuits with 100s of active devices on a single chip are now manufactured and deployed in lightwave communications [17,18]. Leveraging these new fabrication methods, researchers have looked to migrate more novel RF-photonic systems to integrated platforms where they too can benefit from increased speed, reduced cost, improved robustness, and enhanced capability [19–22]. As noted above, one of the more powerful tools one can envision is a fully functioning integrated pulse shaper capable of line-by-line control.
Such a realization becomes more attractive with on-going developments in the field of microroresonator frequency comb generation [4,23], a platform that allows for chip-scale comb generation with 10’s to 100’s of GHz channel spacing, ideal for line-by-line control [6,16,24,25].

On-chip pulse shapers have been pursued on a number of platforms, most notably indium phosphide (InP) [26,27] and silica (SiO2) based material [28]. SiO2-based shapers have been fabricated with very narrow channel spacing, down to 10 GHz, with up to 64 channels for high fidelity phase and amplitude control [28]. However, their reconfiguration speed is limited due to reliance on thermal tuning. InP based shapers on the other hand offer the potential for fast switching using electro-optic effects and offer seamless integration with active components such as on-chip laser sources, semiconductor optical amplifiers (SOAs), and photodetectors. Recent research includes demonstrations of InP-based pulse shapers with channel spacing down to 50 GHz [27], as well as notable progress in designing Arrayed Waveguide Gratings (AWGs) with 10-20 GHz channel spacing [29–31]. Despite these few notable examples, challenges in AWG fabrication have resulted in few high-quality shaping demonstrations in InP. Furthermore, only minimal progress toward realizing the full potential for rapid pulse shaper reconfiguration has been reported. The few studies that do investigate dynamic pulse shaping have modulated only a few lines or even a single line, with poor pulse shaping fidelity [30,31]. Finally, we note that related devices involving arrays of SOAs placed between pairs of AWGs have been implemented in InP for channel selector and optical packet switching applications, e.g [32]. Although dynamic operation has been demonstrated, generally these devices operate in digital fashion with only one wavelength channel at a time; this is in clear contrast to pulse shaping, where simultaneous analog control of all wavelengths is generally desired.

In this contribution we discuss results from a Purdue University and Infinera Corporation collaboration aimed at fabrication and characterization of an InP-based PIC optical pulse shaper and report its application for reconfigurable RF photonic filtering based on shaped optical frequency combs. Our integrated pulse shaper is configured with 32 channels at 25 GHz spacing, with each channel provisioned with a dedicated SOA for line-by-line amplitude control. We first experimentally demonstrate precise amplitude control of optical comb spectra using the SOAs and leverage their fast electro-optical response to rapidly switch between simple shaped waveforms. We then exploit this fast programmable pulse shaping capability to realize high-fidelity RF-photonic filters with greater than 35 dB sidelobe suppression and demonstrate their reconfiguration in less than 1 microsecond. This reconfiguration time is several orders of magnitude improvement over the capability of traditional liquid crystal based pulse shaping devices, from milliseconds down to the ~1 microsecond time scale. Furthermore, such reconfiguration speeds are very difficult to achieve using conventional RF filtering technologies. To the best of our knowledge, our work is the first application of a programmable, integrated line-by-line pulse shaper to RF photonic filtering applications.

### 2. Pulse shaper design and characterization

Fourier Pulse shapers work by dispersing different frequencies of light to unique spatial locations where a complex masking function can be applied to individual channels [1,2]. In bulk pulse shapers the spectral decomposition is typically achieved with a diffraction grating followed by a programmable liquid crystal spatial light modulator (SLM) for masking. The modulated light is then passed through a complementary grating for recombination. In contrast, on-chip pulse shapers typically make use of AWGs to spatially isolate the individual spectral components. Analogous to phased arrays, AWGs rely on multiple beam interference to focus different frequencies of light to different output waveguides [33,34]. The current
A challenge with realizing a high fidelity on-chip pulse shaper is a result of limitations in AWG fabrication. Small errors in the AWG path lengths will add loss, increase crosstalk, and make spectral alignment between the Demux- and Mux- AWGs more difficult. These problems scale with the physical size of the AWG limiting the number of channels and the resolution of the pulse shapers.

The problem of AWG misalignment has been approached in a few novel ways which include placing the two AWGs far apart and using independent heater tuning to align the passbands [26], or by using a single AWG in a reflection architecture [27]. The former has shown promise but increases the device size, is susceptible to environmental fluctuations, and adds to the power dissipation on the chip. The latter keeps a small footprint by utilizing a single AWG but requires an off-chip circulator to recover the shaped output. Another option which has been explored [28], and which we apply here, is to use a loop-back configuration. Here a single AWG acts as both the de-multiplexer and multiplexer, greatly reducing the possibility of channel misalignment.

To perform amplitude shaping we incorporate SOAs in each de-multiplexed channel. SOAs not only provide fast switching capability but also help recover some of the insertion loss of the device. The SOAs were designed to be small with high gain (~20dB) to help keep the chip size small. Multiple epitaxial layers were used to allow for the monolithic integration of active and passive regions on the PICs. The epitaxial layers were grown using Metalorganic vapor phase epitaxy (MOVPE) in a multiwafer reactor. Established growth-etch-regrowth techniques (e.g., as described in [35,36]) were used to monolithically integrate the AWG and SOA functions. Conventional semiconductor fabrication processes were used to precisely define and control the waveguide width, etch depth and sidewall roughness to yield low loss elements within each channel and from channel-to-channel. The die were then singulated into individual die and each one coated with an anti-reflection coating. Finally, the
die were solder-attached to a submount to facilitate testing. An image of the fabricated chip is included in Fig. 1(a). Figure 1(b) shows a schematic representation of the loop-back AWG design. The AWG is a periodic device and has a free spectral range (FSR) of 1.5 THz. The light is input from the bottom left corner and enters a free propagation region where it disperses. The light then travels through the AWG arms following a figure-eight configuration. After going through the AWG the light enters another free propagation region which causes different frequencies to be focused to different spatial locations where they are then individually collected by 32 waveguides which each have an SOA (represented by the blue SOA block in Fig. 1(b)). The 32 waveguides are then multiplexed back into the input of the first free propagation region and are once again routed through the AWG and enter the second free propagation region. Here, the different frequencies of light are all focused to a single output waveguide which is recovered off chip on the right hand side.

To characterize the loss and extinction of the SOA, we aligned a continuous wave (CW) laser with a single channel and recorded the output spectral power when the SOA was at maximum bias (1.8V) and minimum bias (0V). Spectral traces for each test case were taken with an optical spectrum analyzer (OSA) at the output of the shaper and are shown in Fig. 1(c) along with a spectral trace of the input CW laser (green). The single channel extinction between maximum (red) and minimum (blue) bias points is ~20 dB and the single channel loss between the input CW laser (green) and output (red) when the SOA is at maximum bias is ~17 dB, including a double pass through the integrated pulse shaper chip, loss from fiber-to-chip coupling and two external fiber isolators used on the input and output. To measure the loss-variation between channels, we used a broadband amplified spontaneous emission (ASE) source at the input of the pulse shaper and then biased each channel individually at maximum bias. The recorded spectral traces taken at the output of the shaper for each channel are shown in Fig. 1(d). The maximum variation in output power between the 32 channels is ~2 dB. We can gain information on the crosstalk due to random phase errors in the AWG for a given channel, denoted by $\text{CH}_N$ and centered at wavelength $\lambda_N$, by comparing the relative power of $\text{CH}_N$ at $\lambda_N$ to that of all channels $\text{CH}_1$:$\text{CH}_{32}$ at $\lambda_N$. Using this methodology and examining Fig. 1(d), we see the crosstalk floor is close to 15 dB for all channels. Similarly, the nearest neighbor crosstalk can be found by comparing the overlap of adjacent channels $\text{CH}_N$ and $\text{CH}_{N+1}$. Here we find the crosstalk due to overlap of adjacent passbands is ~13 dB for all channels.

2.1 Experimental setup

We now switch to a frequency comb source which allows us to perform line-by-line shaping. Our test setup is depicted in Fig. 2. We utilize an optoelectronic comb source comprised of 5 phase modulators and an intensity modulator which produces a 100-line comb with 12.5 GHz channel spacing [3]. A Differential-Phase-Shift-Keying (DPSK) demodulator is then used to eliminate every other line to achieve our 25 GHz test comb. Light is coupled onto the chip using polarization maintaining lensed fiber and recovered off-chip using standard single-mode lensed fiber. The chip temperature is maintained at 20 deg C utilizing a thermal electric cooler (TEC) with active monitoring from an on-chip thermistor. The SOAs in the pulse shaper are wire-bonded to a ceramic carrier which is accessed by a 32 channel probe card connected to a custom designed high-speed driver board capable of programmatic control. The board is equipped with two registers allowing one to be loaded with a new vector while the other remains active. Simultaneous reconfiguration of all 32 channels is then achieved by switching which of the two registers is active. The output of the active register is connected to an array of 32 digital-to-analog converters (DACs) and subsequent operational amplifiers which provide the necessary SOA drives. The slew-rate of the electronics permits full reconfiguration from maximum SOA bias (1.8V) to minimum (0V) bias in less than 1 microsecond. Although the switching event can be achieved in less than 1 microsecond, the computer latency restricts the minimum time each waveform is active (dwell time) to the millisecond time scale. In order to more rapidly switch back and forth between waveforms, as
we do in our rapid RF-filtering demonstration in Section 3.2, we utilize a Field Programmable Gate Array (FPGA) circuit to control which register is active, permitting a minimum dwell time between switching events of 4 microseconds.

Fig. 2. Optical test setup. An optoelectronic comb generator made up of a continuous wave laser, 1 intensity modulator (IM), and 5 phase modulators (PM) is used to generate a 12.5 GHz frequency comb. A 25 DPSK is then used to cut every other line from the spectrum to create a 25 GHz test comb. The light is coupled to the pulse shaper PIC through PM lensed fiber and recovered off chip using standard lensed fiber. The components shown in green were utilized for the time domain measurements in Section 2(b,d). Here, the external bulk pulse shaper after the comb generator was used to both compress the 25 GHz comb and correct for the phase differences arising from path length differences between channels in the integrated pulse shaper. OSA: optical spectrum analyzer, EDFA: erbium doped fiber amplifier, DPSK: differential-phase-shift-keying demodulator, SOA: semiconductor optical amplifier.

As part of our pulse shaper characterization we include temporal autocorrelation measurements as well as oscilloscope traces of the photodetected waveforms. However, during fabrication no attempt was made to equalize the on-chip path lengths (difference in delay) between different channels, which results in the pulse shaper applying a residual static phase to the different spectral components. Therefore, in order to facilitate the temporal shaping demonstrations, we employed an auxiliary external pulse shaper programmed with a static mask to both compress the test comb source [3] as well as correct for the static spectral phase variation between the different channels. To optimize the auxiliary phase mask, we biased the SOAs at maximum transmission and then using feedback from an autocorrelator we iteratively adjusted the auxiliary phase mask to maximize the second harmonic signal in the autocorrelator. This procedure was performed once, and the resultant phase mask was not changed during the experiment. In future designs we plan to add active phase control to each integrated pulse shaper channel which could be used to correct for the path length difference as well as allow more general arbitrary waveform generation. However, many applications, including our demonstration on RF-filtering in Section 3, are insensitive to such spectral phase.

2.2 Rep-rate multiplication and temporal measurements

To look at the extinction under shaper operation, we perform binary (on/off) shaping of each channel. We start with every channel at maximum bias of 1.8 V and then turn off every other SOA. The output spectra from the integrated pulse shaper for all SOA’s on (25 GHz comb) and every other SOA off (50 GHz comb) are shown in Fig. 3(a), as blue and red, respectively. The individual channel extinctions vary from 14.8 dB to 25 dB with a mean value for all 32 channels of 19.2 dB. We also characterize the temporal waveforms for both the 50 GHz and 25 GHz spectral masks programmed above. The change in the optical frequency spacing between comb lines is expected to correspond to change in the pulse repetition rate. In
particular, eliminating every other comb line should correspond to a doubling of the repetition rate, from 25 GHz to 50 GHz. Autocorrelation traces for both combs are shown in Fig. 3(b), and the photodetected pulse trains recorded with a 50 GHz sampling scope are shown in Fig. 3(c). Both temporal measurements show high quality pulse trains and verify the expected factor of two repetition rate multiplication.

Fig. 3. Measurements for 50 GHz (red) and 25 GHz (blue) flat top comb masks. (a) OSA traces at output of integrated pulse shaper, (b) Autocorrelation traces, and (c) photodetected electrical waveforms taken with 50 GHz sampling scope.

2.3 High fidelity line-by-line shaping using feedback

Up to this point our demonstrations have focused on binary gain control with our SOAs. Here we highlight the shaper’s ability to impart fine gray-scale control. We intentionally generate a comb with poor spectral flatness and program the pulse shaper to equalize the channels: although optoelectronic combs can be made very flat, future integrated solutions may take
advantage of microresonator combs which often exhibit strong spectral variation. Using computer control, assisted by feedback from an OSA, we run an iterative process to flatten the spectral envelope [37]. After running 5 iterations of the program, the maximum deviation of the 32 shaped comb lines improves from 10.49 dB to 0.42 dB, while the standard deviation of the comb line amplitudes is improved from 2.48 dB to 0.099 dB. Figure 4(a), shows the input comb (blue) overlaid with the output of the pulse shaper (red) after shaping. Figure 4(b) shows a vertical zoom of the shaped spectrum (red) and its deviation from the target (black). Visualization 1 depicts the evolution of the spectral profile during the iterative shaping process.

Precise spectral tailoring is important for many areas in RF-photonics. This is especially paramount in RF photonic filtering where small deviations from the target profile can degrade the shape and reduce the side-mode suppression of the filters as we will demonstrate later in Section 3.

2.4 Rapid reconfiguration

One of the key advantages of using our SOA design in InP is the capability to quickly switch between waveforms. Using our driver card we test the switching speed of a single channel. We align a single frequency laser to one of the channels and use the SOA to switch on and off the channel bias. We measure the output with a 50 GHz photodetector and record the switching event using a 20 GHz real-time scope. The 90/10 fall time is between 400 and 500 ns. Figure 5 shows the optical rise and fall times (blue) overlaid with a plot of the electrical drive signal (red). These results indicate that our switching speed is limited by the electrical drive. In fact, the optical response is actually faster than the electrical drive, which is understandable because the diode-like response of the SOA acts to sharpen the overall response. Provided with faster electronic control, we believe the SOAs will track the drive circuit at switching times down to tens of nanoseconds.

![Fig. 5. Single channel switching speed measurement comparing SOA electrical drive signal (red) to the photodetected optical output (blue). (a) SOA switched from maximum bias to minimum, and (b) minimum bias to maximum bias. 90/10 rise fall time of optical signal is ~400-500 ns.](image)

Next we look at the simultaneous reconfiguration speed of all 32 channels at once by rapidly switching between a 25 GHz and 50 GHz RF waveform. For this switching experiment, we first program the integrated pulse shaper to optimize the spectrum for a flat top profile similar to Fig. 3(a), shown in blue. Then using computer control, we turn off every other SOA simultaneously to achieve 50 GHz channel spacing [Fig. 3(a)] shown in red. The optical output of the integrated pulse shaper is then sent to a 50 GHz photodetector to be converted into an electrical waveform. Figure 3(c) shows the static recorded electrical...
waveforms sampled by a 50 GHz sampling scope. To capture the dynamics of the switching event, we also sent the output of the photodetector to a 63 GHz real-time oscilloscope (Keysight DS0X96204Q). The measured time domain trace and corresponding spectrogram for the waveform transitions, 25-to-50 GHz and 50-to-25 GHz, are shown in Fig. 6(a) and Fig. 6(b) respectively. Below each temporal snapshot are their respective spectrograms, which were processed offline using a 40 ns Hamming window. From the spectrograms, we can clearly see the waveform transition in both cases takes place in less than half a microsecond, matching the single channel results from above. The insets (i) and (ii) next to Fig. 6(a), and likewise insets (iii) and (iv) next to Fig. 6(b), show the magnitude squared (RF power) from the calculated short-term Fourier transforms which correspond to the highlighted slices in the scope traces. The slices are located roughly 1 microsecond before and after each switching event. Examining insets (ii) and (iii), which correspond to the time when the 50 GHz waveform is present, we can see greater than 20 dB extinction in the 25 GHz tone—closely matching the channel extinction shown in the optical spectrum in Fig. 3(a).

Fig. 6. 32 channel switching experiments when shaper mask is changed from 50 GHz to 25 GHz (a), and 25 to 50 GHz (b). The optical waveforms were detected with a 50 GHz photodetector and measured with a 63 GHz realtime oscilloscope. The spectrograms were processed offline using a 40 ns Hamming window. The figure insets (i and ii) and (iii and iv) show the magnitude squared of the short-term Fourier Transforms which correspond to the highlighted windows in the temporal traces of (a) and (b), respectively. The highlighted sections occur roughly 1 microsecond before and after each switching event.

3. RF filtering demonstrations

Radio frequency filtering plays a pivotal role in wireless communication, imaging, and sensing technologies. Recently, driven by data intensive applications like broadband wireless, high resolution imaging, and sensing, there has been an increased demand for bandwidth, which has posed challenges for traditional filtering architectures. These bandwidth demands
can be more easily met if the signals are processed in the optical domain [8]. Our focus here is to provide a simple application example that utilizes our integrated pulse shaper as a programmable filter. The aim is both to critically test the performance of the integrated pulse shaper and to highlight the benefits line-by-line shaping and rapid reconfigurability can provide over conventional RF-filtering approaches; including the ability to tune the filter passband frequencies with negligible effect on the filter lineshape or gain, and the ability to reconfigure the passband shape on a microsecond time scale.

A popular method to implement RF-Photonic filters is based on a tapped-delay line structure [13]. In the simplest case, an RF signal is first modulated onto the optical carrier and then split between different delay lines. The split signals are then recombined and detected by a photodiode to produce the RF waveform. The resulting filter transfer function can be characterized by a finite impulse response (FIR), allowing for the design of arbitrary amplitude filters. However, scaling these schemes to a large number of filter taps is difficult. Other approaches which utilize multi-wavelength sources can be more easily scaled [14,38–40]. In these schemes the RF signal is modulated onto the multi-wavelength carrier and then passed through a single delay line. The differential delays between the multi-wavelength signals (i.e. filter taps) are then applied through fiber dispersion. The amplitudes and delays of the filter taps can be controlled by adjusting the optical powers of the multi-wavelength signals and the length of the dispersive fiber, respectively. Adding a programmable pulse shaper to the setup allows the filter to be dynamically adjusted or reconfigured. Such tuning is difficult using conventional filtering architectures and is important for emerging applications like cognitive radio [41] and software-defined radio [42] which can benefit from the added flexibility.

In this contribution, we adopt an FIR comb-based filtering architecture that was previously investigated in [15]. In addition to a frequency comb, pulse shaper, and delay line, this scheme introduces an interferometric configuration with balanced detection which enables simple tuning of the filter passband and allows for simultaneous reduction of RF loss and noise suppression. As with similar programmable multi-tap filtering architectures, the quality of the RF filter response, in terms of side-lobe suppression and stopband attenuation, is directly tied to the accuracy of the spectral shaping [39,43]. For example, in order to achieve a Gaussian RF-filter with greater than 40 dB side-lobe suppression, the spectral envelope must not deviate from the target by more than a few tenths of a dB.

Our RF filtering setup is shown in Fig. 7 and explained briefly in the following. More detailed information on the filtering configuration can be found in [15]. We utilize the same 25 GHz optoelectronic comb source as described in Section 2.1. The comb is then sent through the integrated pulse shaper where its amplitude is modified to form the desired filter shape. The apodized comb is then amplified in an erbium doped fiber amplifier (EDFA) before being split into a delay and modulation path via a 10:90 optical splitter. 10% of the comb power is directed to a variable delay line (VDL); 90% of the comb is directed to the Mach-Zehnder modulator (MZM), which is biased at the minimum transmission point and driven by the RF signal to be processed. The signals from the two arms are then orthogonally combined by a polarization beam combiner (PBC). The combined light then travels through a dispersive element implemented by a spool of dispersion compensating fiber (DCF) with a dispersion value of $-1254 \text{ ps/nm}$ at 1550 nm. To reduce size, chirped fiber Bragg gratings could be used instead of dispersive fiber. After the fiber delay, a polarizing beam splitter (PBS) is used to create two complementary signals that are then detected by a balanced photodetector (BPD). The 25 GHz comb spacing, in concert with the dispersion specified above, translates into a delay of 250 ps between adjacent taps (comb lines). As explained in [15,39,43,44], the RF filter response is periodic with a free spectral range (FSR) of 4 GHz, given by the inverse of the tap spacing. Within each FSR, there are two passbands, one corresponding to the upper sideband and the other to the lower sideband in our double sideband modulation scheme. One of the passbands can be suppressed if one adopts single
sideband modulation, as in [39,43]. The passband frequencies tune in proportion to the delay imbalance of the interferometer divided by the dispersion (expressed in units of ps\(^2\)), with one passband tuning to higher RF frequencies, the other to lower RF frequencies.

Fig. 7. RF–filtering setup. The spectral profile of the 25 GHz comb source is tailored in the integrated pulse shaper using feedback from an OSA to create different filter shapes. The tailored spectrum is then amplified in an erbium doped fiber amplifier (EDFA) and split into an interferometric configuration. The top path of the interferometer has a variable delay line (VDL), which can be used to tune the center frequency of the passbands. The bottom path incorporates a Mach-Zehnder modulator (MZM) which modulates the RF signal to be filtered onto each of the optical carriers. The two interferometer arms are then recombined in a polarization beam combiner and travel through a length of dispersion compensating fiber (DCF) which imparts a differential delay between the filter taps. Finally, the optical signal is split using a polarization beam splitter and both copies are detected using a balanced photodetector (BPD). A vector network analyzer is used to measure the RF gain vs. frequency response.

Note that the RF filter response is insensitive to the spectral phase of the input comb feeding the interferometer structure. Therefore, in the geometry of Fig. 7, where the integrated pulse shaper is placed prior to the interferometer (prior to the yellow box), only the ability to perform spectral amplitude shaping plays a role. As noted in Section 2.1, the phase response of the pulse shaper does not affect the RF filtering function. Therefore, the external pulse shaper used for phase control in the setup of Fig. 2 is unnecessary and is not used for the RF filtering experiments shown in the following.

3.1 High fidelity RF filters

Precise spectral tailoring is important for many areas of RF photonics, but is paramount in comb-based RF photonic filtering. Using the iterative procedure described in Section 2.1, we program three spectral filter masks, Flat-Top, Hamming, and Gaussian. The resultant spectra are shown in blue in Figs. 8(d)-8(f), along with the target spectral profile in red. The relative shaping error between the measured and target comb shapes are shown above their respective spectra in Figs. 8(a)-8(c). Using a vector network analyzer we measure the filter response for each case, with the RF-spectra plotted in green in Figs. 8(g)-8(i), along with the simulated response in black. The detailed filtering results are tabulated in Table 1. The Gaussian and Hamming filter shapes achieved the greatest sidelobe/stopband performance (compared to the flat-top spectrum) whereas the flat-top filter achieved highest selectivity. The relationship between the filter selectivity (measured by the filters’ 3 dB bandwidth) and the sidelobe/stopband performance, are as anticipated from their respective spectral shaping functions and demonstrate the expected trade-offs of spectral shaping: apodization sacrifices optical bandwidth to achieve a smoother spectrum. The RF gain, which is a very important parameter for potential applications, varies from −4.3 dB to −3 dB for the different filter shapes. Although the gain values are slightly below unity, low loss values like these are seldom achieved in RF photonic filtering experiments. As explained in detail in [15], we attribute the favorable RF loss performance to the use of an EDFA to boost optical power followed by the interferometer structure, which provides for differential detection eliminating...
most of the additive noise from the EDFA. The 1.3 dB of gain variation between the different filter shapes can be attributed to different amounts of optical output power for different comb shapes.

|                | Flat          | Hamming      | Gaussian     |
|----------------|---------------|--------------|--------------|
| Shaping Error  | <0.2 dB       | <0.32 dB     | <0.32 dB     |
| Error (std)    | (0.11 dB)     | (0.14 dB)    | (0.183 dB)   |
| RF Gain        | −4.3 dB       | −3.5 dB      | −3 dB        |
| 1st Sidelobe Supp. | >15.5 dB   | >34.9 dB     | >35.8 dB     |
| Stopband Attn. | >24.7 dB      | >35.6 dB     | >36.2 dB     |
| 3dB Bandwidth  | 130 MHz       | 170 MHz      | 240 MHz      |

Fig. 8. Optical shaping and RF filtering results for Flat Top, Hamming, and Gaussian filters. (a-c) the shaping error between the target optical spectral profile and measured profile after spectral shaping, (d-f) the measured optical spectra-blue and target profile-red. Finally, (g-i) show the measured RF-gain vs frequency for each RF filter shape in green along with the expected result which was calculated using the recorded optical spectrum.

In addition to precise and flexible control of the filter shape with the pulse shaper, our interferometric architecture allows for independent tuning of the filter passband location by adjusting the VDL in the upper arm of the interferometer. Figure 9 shows the RF-filter shape and location for three different delay set points on the VDL. For each delay, we re-loaded and re-applied the saved masking functions that were used to create the filter shapes in Fig. 8. Not only do these results show the delay tuning has minimal effect on the filter shape, but they also highlight that the pulse shaper masks (SOA set points) can be stored, switched, and re-applied without loss in the shaping fidelity.
3.2 Rapidly reconfigurable RF filtering

We now leverage the fast switching speed of the SOAs to rapidly reconfigure the filter shapes. Our test setup is depicted in Fig. 10(a). Here an FPGA is utilized to select which one of two registers is active in the driver board. The registers were preloaded with the Flat top and Hamming shaping vectors which produced the RF filters characterized in the previous section. For our first demonstration we send a single RF tone into the filter scheme. The filter passband location, which is determined by the amount of dispersion in the delay line, is centered around 3.08 GHz. The RF tone at the input of the filter setup is chosen to be 3.19 GHz, a frequency location which corresponds to a 10 dB difference between the filter response of the Hamming and Flat top filter shapes. The passbands for both the Hamming and Flat Top filters are shown in Fig. 10(b) along with an orange marker indicating the location of the 3.19 GHz RF tone. We then use the shaper with FPGA control to rapidly switch between the two filter shapes and record the photodetected RF-waveform on a 20 GHz real-time oscilloscope. Because the RF input signal is positioned away from the passband center frequency,
switching between the two filter shapes—which have different bandwidths—will result in a modulation of the detected signal. The recorded temporal trace and the calculated spectrogram are shown in Fig. 11(a). The dwell time between filter switching events is approximately 4 microseconds and the transition takes place in less than 1 microsecond. As expected, the extinction of the 3.19 GHz tone between the two filters is roughly 10 dB. This confirms the filter shapes keep their fidelity even when rapidly cycled back and forth.

For the next experiment we multiplex an additional RF tone centered at 3.08 GHz at the input of the filter setup. Once again, we switch between the two filter shapes and record the output on the real-time scope. The resultant waveform and spectrogram are plotted in Fig. 11(b). Here the power in the tone centered at 3.08 GHz should remain constant as it is located in the center of both filter passbands. The slight fluctuation in the power of the RF signal at 3.08 GHz can be attributed to the difference in RF gain between the two passbands as indicated in Table 1. Figures 11(c) and 11(d) show zoomed-in traces of highlighted regions in Fig. 11(b), which correspond to when the Hamming filter and Flat Top filters are active, respectively. Examining Fig. 11(c), reveals a slow modulation in the envelope of the detected waveform with a period of ~9 ns caused by the interference of tones at 3.19 GHz and 3.08 GHz both being present. In contrast, when the Flat Top filter is present, as shown in Fig.
11(d), the 3.19 GHz tone has been sufficiently suppressed to the point where no interference is visible in the detected waveform.

4. Discussion

We have demonstrated a 32 channel integrated pulse shaper that is capable of simultaneous high-fidelity pulse shaping and rapid reconfiguration in less than 1 microsecond. Our design incorporated a single AWG to ensure matching between multiplexing operations which allowed us to achieve 25 GHz channel spacing with low 15 dB crosstalk. We showed that inter-channel SOAs could be used to perform precise gain control while also reducing the insertion loss of the device. The shaper not only closely parallels bulk products in terms of shaping fidelity, but has a reduced form factor and provides several orders of magnitude improvement over traditional pulse shapers in terms of update rate.

We experimentally evaluated the shapers precise spectral control by tailoring RF-photonic filters with greater than 35 dB sidelobe suppression and then rapidly switched between filters every four microseconds. Our RF-filter demonstrations highlighted key benefits to photonic filtering schemes, which include both passband tuning without degradation in filter shape, as well as the ability to rapidly select between multiple high-frequency signals in close proximity. These demonstrations highlight photonic filtering qualities which are difficult to implement using traditional electronic based filtering architectures.

As data demands continue to soar, greater flexibility in network architectures will be required in order to handle the additional bandwidth and increased signal complexity. Optical solutions applied to the generation and processing of RF signals offer a solution to not only manage the bandwidth demands with ease, but also enable seamless integration with established fiber networks, allowing for low-loss long-distance transport with immunity to electromagnetic interference. Further, photonic schemes which utilize programmable pulse shaping technology gain additional flexibility in terms of optimization and reconfiguration. Such architectures are important for emerging applications like software defined, cognitive, and multi-standard radio.

Although our pulse shaper was the only integrated component in our filtering scheme, other necessary components have been recently investigated. For example, frequency combs generated on silicon photonic chips have served as the optical source in RF photonic filtering demonstrations by us [16] and others [25], and a silicon photonic crystal waveguide was employed as a dispersive element in the filtering arrangement presented in [45]. In the future we plan to add line-by-line phase control to complement the SOA gain control. With a phase and amplitude pulse shaper, the delay tuning of the RF filter passband center frequency (demonstrated here at slow speeds using a variable delay line) could be programmed directly on the pulse shaper using the fact that linear spectral phase is equivalent to delay [46], allowing for simultaneous rapid reconfiguration of the passband shape and center frequency. Such reconfiguration and tuning are difficult to achieve using conventional approaches even at slow tuning speeds. Continued advancement in photonic integration may eventually make fully integrated solutions not only possible, but cost effective.

Funding

Defense Advanced Research Projects Agency (DARPA) (W31P40-13-1-0018) from AMRDEC. HJK received funding from the National Research Foundation of Korea (NRF-2014R1A6A3A03059647)