RF arbitrary waveform generation using tunable planar lightwave circuits

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We demonstrate photonic ally-assisted generation of RF arbitrary waveforms using planar lightwave circuits (PLCs) fabricated on silica-on-silicon. We exploit thermo-optic effects in silica in order to tune the response of the PLC and hence reconfigure the generated waveform. We demonstrate the generation of pulse trains at 40 GHz and 80 GHz with flat-top, Gaussian, and apodized profiles. These results demonstrate the potential for RF arbitrary waveform generation using chip-scale photonic solutions.

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1. Introduction

Due to the extensive applications of ultrabroad-bandwidth radio-frequency (RF) pulses in several domains such as radar systems [1], wireless communications [2], and remote sensing [3], it is necessary to find a flexible and low-cost method to generate arbitrary RF waveforms. The bandwidths needed for these applications range from the ultra-wideband domain (3.1–10.6 GHz) to the mm-wave regime (~30–100 GHz). Due to limitations in digital-to-analog conversion technologies, conventional electronic approaches are not able to generate RF waveforms with very high bandwidths. Photonically-assisted RF waveform generation is a powerful technique to overcome the bandwidth limitations of electronics. Moreover, it has the advantage of direct data transmission in the optical domain to a remote location and flexibility in reconfiguring the synthesized waveforms.

The general schematic for photonic ally-assisted RF arbitrary waveform generation using optical pulse shapers is shown in Fig. 1. This method is based on generating a temporal optical waveform with desired features from an input pulse using an optical pulse shaper, and then converting the shaped waveform to an electrical signal using a broadband photo-detector. The pulse shaping process can be accomplished using time domain or frequency domain techniques. One well-established technique is using pulse shapers either in bulk or arrayed waveguide gratings for shaping the spectra of a broadband coherent or incoherent source through Fourier synthesis and converting it to the time-domain using frequency-to-time mapping [4–6]. Another bulk-optic approach is the direct space-to-time pulse shaper (DTS) which was demonstrated in [7]. The DTS consists of a diffractive optical element (DOE) which splits a single input beam into multiple, nearly equal intensity, spatial spots. Subsequent to the DOE, there is a spatial mask to adjust the period, spacing, position, and amplitude of the spots. The main advantage of bulk-optic methods is the ability to tune precisely the spectral components. However, they require a very short input pulse to have a wideband spectrum and they have the common drawbacks which include strict alignment requirements, low power efficiency, and sensitivity to the environment. Pulse shaping can also be performed using fiber Bragg gratings (FBGs). For example, Shen et al., presented a grating and delay structure for amplitude weighting and time delaying the optical samples [8] while Wang et al. demonstrated optical pulse shaping using a single spatially discrete chirped fiber Bragg grating [9]. Another technique for pulse shaping is synthesizing an optical pulse waveform by coherently superposing a set of properly delayed replicas of the input pulse, e.g., using a conventional multi-arm interferometer [10].

An on-chip integrated pulse shaper is a desirable solution to overcome the limitations commonly associated with conventional bulk optics pulse shapers. In a recent work, a spectral pulse shaper is integrated by cascaded multiple-channel micro-ring resonators on a silicon-on-insulator platform; the temporal waveform is then obtained using frequency-to-time mapping [11]. By this approach, it is possible to completely control the RF waveform, including amplitude, frequency, and phase. However, ring resonators require tight control over the fabrication process; otherwise, errors can degrade significantly their response. Another attempt for integrated photonic microwave devices is the programmable photonic microwave filter with tunable inter-ring coupling [12]. This device is fabricated using InP/InGaAsP material and is able to generate 2nd and 3rd order coupled ring filters. The tunability is achieved by tunable couplers and phase modulators. Cascading several stages of the unit...
cells allows for more elaborate filter shapes with better extinction ratio; however, the fabrication process is more complicated compared with the silica PLC platform.

Other approaches for photonically-assisted RF waveform generation that do not require pulse shapers exist [13–16]. For example, conversion of phase modulation to intensity modulation with spectral filtering can be exploited to generate monochromes. Although these approaches can generate RF waveforms, they can be complex or can generate only a limited range of waveforms. In this paper, we report on the use of silica-on-silicon planar lightwave circuits (PLCs) for generating RF arbitrary waveforms at high bandwidths. The PLC implements a multi-tap filter with a free spectral range (FSR) of 80 GHz; moreover, it is tunable using thermo-optic effects. Our device is capable of generating a variety of waveforms with bandwidths up to 80 GHz. Compared with previously demonstrated techniques, our approach is relatively simple and employs standard silicon-based processing. It does not require any nonlinear effects so that the power consumption is low, and tunability is readily achieved by changing DC voltages applied to the PLC (to control thermal effects). Finally, the PLC offers a high level of integration and a good overlap with optical fiber, which minimizes the insertion loss.

2. Planar lightwave circuit

Our approach for photonically-assisted arbitrary RF waveform generation is based on a pulse shaper that can generate arbitrary temporal waveforms at high repetition frequencies. The pulse shaper is fabricated using silica-on-silicon PLC technology. Fig. 2(a) shows the schematic of the PLC device which is a 12 tap finite impulse response (FIR) filter that performs both phase and amplitude filtering. We have used a lattice-form Mach–Zehnder interferometer, i.e., 12 stages of cascaded interferometers, to implement this filter. Each stage consists of two arms with a path length (arm length) difference that determines the filter FSR. In our device, the FSR is 80 GHz, which corresponds to a temporal tap separation of 12.5 ps (note that we can fabricate devices with different FSRS by properly controlling the path length difference in order to match the target application and required bandwidth of the RF signal). The output pulse train from the PLC is the time domain convolution of the input pulse train and the filter impulse response $h(t)$ [17]:

$$a_{out}(t) = a_0(t) \otimes h(t) = a_0(t) \otimes \sum_{n=-\infty}^{+\infty} |h_0(n'T_{FSR})| e^{j\delta_0}(t-nT-n'T_{FSR})$$

where $a_0(t)$ is the complex envelope of an individual pulse in the input train, $T = 1/R$ is the period of the input pulse train, and $T_{FSR} = 1/FSR$ is the unit delay of the SP filter. The filter impulse response $h(t)$ can be expressed in terms of its amplitude $|h_0(n'T_{FSR})|$ and phase $e^{j\delta_0}$ terms at the (sampling) time instants $t = n'T_{FSR}$. The amplitude of each pulse in the output train is defined by the term $|h_0(n'T_{FSR})|$, i.e., the magnitude of the filter impulse response at the discrete time instants $n'T_{FSR}$. Therefore, any user-defined output amplitude pattern can be generated by controlling the magnitude of the filter impulse response at the $N$ discrete time instants $n'T_{FSR}$. Similarly, the phase of each output pulse is defined by the term $e^{j\delta_0}$. Therefore, any user-defined output phase pattern can also be generated by controlling the phase of the filter impulse response at $t = n'T_{FSR}$. By tuning the filter response, we can reconfigure the system to generate arbitrary waveforms.

Fig. 2(b) shows the waveguide cross-section. The device is fabricated using plasma-enhanced chemical vapor deposition (PECVD) and reactive ion etching (RIE). The top cladding layer is made of borophosphosilicate glass (BPSG) using doping levels and annealing conditions to give a refractive index matching that of the lower cladding $n_{cladding} = 1.4456$ and a planar top surface for subsequent addition of heating electrodes and contacts. The refractive indices of the core and cladding are $1.4700 \pm 4 \times 10^{-4}$ and $1.4456 \pm 4 \times 10^{-4}$ respectively at a wavelength of 1550 nm. The waveguide cross-section is designed to be $3.5 \mu m \times 3.5 \mu m$. The curved portions of the circuit have a radius of at least 2 mm in order to minimize bending losses. The $2 \times 2$ couplers are based on a multimode interference (MMI) design. The process for tuning the filter response via thermo-optic effects is achieved by adding a chrome heater on one arm of each Mach–Zehnder. The heater strips
are 7 μm in width, 5 mm in length, and are positioned at least 4 μm above the top surface of the waveguide core to ensure that they are optically isolated from the propagating light. Gold contacts were then patterned using 30 nm Ti/470 nm Au and wire-bonded to connector pins on a device carrier. Optical characterization of simple test structures based on single stage MZIs demonstrated that a π phase shift could be routinely achieved with I = ~10 mA and P = ~200 mW. Furthermore, we did not observe thermal cross-talk between devices with heaters for a separation as small as 200 μm. In our device, the minimum spacing between heaters is 2.75 mm.

3. Experimental setup and results

Fig. 3 shows the experimental setup for photonically-assisted RF waveform generation. The input signal comprises pulses approximately 2 ps in duration at a repetition rate of 2.5 GHz at 1555 nm. We use an EDFA to compensate the insertion loss of the PLC device which is about ~14 dB (this is the fiber-to-fiber loss). Optical fibers are used to butt couple the light in and out of the device and the fibers are aligned to the waveguides using a microscope and IR camera. We also use a polarization controller (PC) to optimize the state of polarization (SOP) of the input signal which maximizes/optimizes the output waveforms. The signal at the output of the chip is first amplified using an EDFA and then converted to an electrical RF signal using a photodetector with 100 GHz bandwidth. The photodetector is connected to an electrical sampling module having a bandwidth of 80 GHz for viewing on a digital oscilloscope. In order to generate different waveforms, 12 individual DC power supplies are connected via gold contact pads to the 12 chrome heaters of the device. We obtain the different waveforms by adjusting these voltages through trial-and-error, while observing the waveforms on the oscilloscope (no specific algorithm or automated feedback loop was used, however, it is possible to include a feedback loop for automated adaptive generation). We have performed measurements on single-stage Mach–Zehnder switches fabricated on the same chip using the same processes to characterize the dynamic response of thermal switching. The rise and fall times of the switching response are 180 μs and 422 μs, respectively. We expect the response time of the 12-loop device to be similar, thereby supporting reconfiguration speeds on the order of 1 ms.

Since we are not able to measure the RF spectrum of the waveforms at 80 GHz directly using an electrical spectrum analyzer, we use an all-optical RF spectrum measurement approach [18]. Fig. 4 demonstrates the principle of the measurement, which is based on mapping the temporal intensity of the signal under test (at \(o_0\)) into the electric field of a CW signal (at \(o_0\)) via cross-phase modulation in a nonlinear medium, e.g., highly nonlinear fiber (HNLF). The spectrally broadened signal at \(o_0\) contains information on the RF spectrum of the signal under test. Thus, by measuring the optical spectrum of the CW signal, we can obtain the RF spectrum of the signal under test. Based on the parameters of the HNLF used and the wavelengths of the signal under test and CW laser, the bandwidth of our all-optical RF spectrum analyzer was measured to be ~1087 GHz.

Fig. 5(a) shows the generation of a flat pulse train at ~80 GHz and the corresponding RF spectrum (as measured in the optical domain using a high-resolution optical spectrum analyzer). The discrete lines in the RF spectrum are separated by about 2.5 GHz, which corresponds to the repetition rate of the input pulses. The side-lobe suppression of the flat pulse train is about 53 dB. As mentioned previously, we are able to control precisely the amplitude of the individual peaks in the output pulse train by tuning the PLC. This capability has several applications such as apodizing the envelope of the output train to suppress the level of the side-lobes of the RF spectrum. For example, we are able to suppress the side-lobes to 68 dB by generating pulse trains with Gaussian-like envelope; Fig. 5(b) shows the Gaussian-like pulse train in the time domain, along with the corresponding RF spectrum.

We also generated various waveforms that are generally difficult to generate using electronics at this bandwidth. Fig. 5(c) and (d) are the saw-tooth waveforms at ~80 GHz and Fig. 5(e) is the saw-tooth at 40 GHz. These waveforms have applications in various domains such as optical frequency shifting (serrodyne frequency translation) or radar systems [19]. Note that the small variations in the central frequencies of the RF waveforms are due in part to fabrication errors in the path length difference in the Mach–Zehnder interferometers.

4. Discussion and summary

In this work, we have demonstrated photonically-assisted generation of arbitrary RF waveforms. Our approach is based on PLCs fabricated using silica-on-silicon technology. Our device is able to generate waveforms with a maximum bandwidth of 80 GHz; by tuning the device, we have demonstrated various waveforms at 40 GHz and 80 GHz. A polarization controller at the input of the chip was used to optimize the SOP of the input signal in order to optimize the output waveform. We observed some polarization dependence, which we believe is largely due to the influence of the Cr heater strips placed over the waveguides. Recent work shows that by increasing the separation between the Cr heater strips and the waveguides (i.e., increasing the cladding layer thickness) as well as etching grooves into the top of the device structure, we can reduce this polarization dependence (in part due to stress relief); however, a detailed discussion including various design trade-offs is beyond the scope of this paper.

Overall, compared to other demonstrations of photonically-assisted RF waveform generation, our approach is simple to implement, does not require nonlinear optical effects or long lengths of dispersive media to achieve frequency-to-time mapping, and most importantly, is integrated, thereby avoiding the problems that are common to free-space techniques. The total fiber-to-fiber loss of our device is about 14 dB, which is significantly lower compared to the other integrated approaches based on high index contrast platforms.
Fig. 4. Principle of all-optical RF spectrum analyzer [13].

Fig. 5. Generation of different waveforms.
Furthermore, the process of tuning this device can be easily automated by providing a look-up table for the required DC voltage for each pad to generate various waveforms. Finally, we can design and fabricate the PLC to have a specific FSR (e.g., 60 GHz or beyond 80 GHz) to meet the needs of various applications. We believe the integrated nature, the simplicity in tuning, and the possibility in generating a variety of waveforms with this device make it an ideal tool for a wide-range of RF applications.

References