Silicon Photonics Enabled Hyper-Wideband RF Receiver With >85% Instantaneous Bandwidth

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Abstract—We demonstrate the first-ever silicon photonics enabled hyper-wideband RF spread-spectrum link. A hybrid III/V-silicon photonic mode-locked laser encoded with a four-channel silicon photonic phase encoder is used to generate optical carriers that coherently demodulate a received RF signal spanning an instantaneous bandwidth greater than 85% of the center frequency (12/14 GHz). This allows low-speed (<3 GHz) electronics to be used in place of the traditional costly and high-power wide-bandwidth electronics used in an all-electronic hyper-wideband link. In addition, integrated highly tunable optical notch filters are successfully used to reject unwanted narrowband interference, with rejection ratio and tunability that surpass conventional wireless technology.

Index Terms—Silicon microwave photonics, hyper-wideband RF, data obfuscation, spread-spectrum.

I. INTRODUCTION

INTEGRATED photonics promises to bring the advantages of optics, particularly large bandwidths and wide-band tunability, to the aid of domains traditionally served by bulky electronics. Common difficulties with bulk and fiber optics such as lack of phase stability and expensive and laborious alignment prevent large-scale highly complex systems to be built in a low-cost and mechanically stable way. By overcoming these challenges, integrated photonics opens up new possibilities for optics and leads to new applications of light beyond merely shrinking existing optical systems to smaller sizes. One such application is in the realm of hyper-wideband wireless communication.

Traditional radio-frequency (RF) wireless systems operate with very high spectral power density in narrow frequency bands. These systems are highly susceptible to interference from other signals, or malicious jammers, that occupy the same frequency band. A traditional solution to circumvent narrowband interference is to spread this narrowband signal over a large bandwidth, termed spread-spectrum RF [1]. For example, an ultra-wideband RF system spreads a narrowband RF signal over an instantaneous bandwidth of >500 MHz. The resultant transmitted signal occupies a large bandwidth and exhibits a very low spectral power density. Interfering narrowband signals can be filtered out with a tunable filter without losing much power from the desired received signal. In addition, the low spectral power of these systems can be used to obfuscate data transmission while their hyper-wide bandwidth can support multiple users through code division multiplexing (CDMA) and can be designed to be highly jam resistant through large processing gain [2]. To increase data rates and processing gain ever larger RF bandwidth is required. However, with the mass proliferation of radios, free radio-spectrum is increasingly difficult to obtain.

Hyper-wideband RF systems are defined as wideband RF systems that occupy an instantaneous bandwidth >10 GHz [3]. Such systems could enable high data-rates and massive jamming rejection due to high processing gains, allowing them to operate in already crowded spectrum bands. Unfortunately, such wideband and high frequency systems [4] are very complex and costly to implement as they require high-speed electronics (>20 GHz) and suffer from a lack of available tunable filters required to reject unwanted narrowband interference. The bulkiness of electrical wideband systems mainly comes from the requirement of the high-Q RF filter. Tunability in an electrical filter while maintaining high Q and high linearity is typically achieved by mechanical tuning and results in limited tuning range and large size [5], [6].

Silicon microwave photonics is an integrated optoelectronic platform that can be used to generate and manipulate RF signals in the optical domain [7]. By using a comb laser source, multiple RF carriers can be simultaneously generated without the need for high-speed electronics. Narrow bandwidth silicon photonic filters allow individual carriers to be independently addressed and modulated. In addition, silicon photonic...
bandpass and bandstop filters have unparalleled tunability (>1THz) that allows for narrowband filtering [8] of unwanted signals in a compact form-factor that is not possible in the electrical domain.

In this paper, we present our results implementing the first ever hyper-wideband RF receiver using an integrated optoelectronic platform [9]. A silicon-photonics platform is utilized that provides optical processing for spread spectrum correlation as well as integrated ring notch filters for narrowband interference rejection. We demonstrate 6 dB of optical coding gain, 27 dB of interference rejection with integrated notch filters, and error-free transmission up to 3Gbaud over a wireless link.

II. SYSTEM OVERVIEW

The full RF transmission system is shown in Fig. 1. While an RF photonics system similar to the receiver could be used to implement the transmitter, the focus of this work was the design and implementation of the RF receiver. To test a full link, we used a high-speed arbitrary waveform generator (AWG), followed by a high-power RF amplifier and a broad-band antenna [10] for the transmitter. The AWG directly produced the hyper-wideband RF signal consisting of four identically modulated signals with RF carriers at 9 GHz, 12 GHz, 15 GHz, and 18 GHz respectively. Each carrier was phase encoded with either a zero or pi offset and all carriers modulated with an identical baseband BPSK signal. This effectively spread the baseband BPSK signal over an instantaneous bandwidth of more than 12 GHz.

The receiver consists of a broad-band antenna followed by a low-noise amplifier which drives a lithium niobate Mach-Zehnder modulator. These three components are the only components in the receiver that require a wide electrical bandwidth. The modulator up-converts the RF signal onto a 1536 nm CW optical carrier generated using a commercial external-cavity laser. This up-conversion process creates both an upper and lower sideband signal of which the upper side-band and CW carrier are filtered out using a 15 GHz single side-band optical filter. The resultant signal is then beat against an optical local oscillator (LO) consisting of four phase-encoded comb lines frequency matched to the carrier frequencies of the up-converted RF signal. If the relative phase encoded on the LO comb lines matches the relative phase encoded on the corresponding RF carrier frequencies, the data is constructively correlated to baseband [11]. If the wrong code is used for the LO, the baseband converted data destructively interferes leaving no signal on the output. For successful correlation, the output electrical signal is the low-bandwidth baseband signal modulated on the transmitter’s RF carriers. The following baseband amplifiers and analog-to-digital converters only need to have a bandwidth capable of supporting this narrowband signal.

III. SILICON HYBRID MODE-LOCKED-LASER

To properly convert the received hyper-wideband RF signal down to a narrow-bandwidth baseband signal, it must be mixed with a proper local oscillator (LO) signal on the receiver. Since the transmitter uses four RF carriers to spread out the baseband BPSK signal, four identically spaced carriers must be generated on the receiver. In a traditional RF system, these high-frequency carriers would be generated with separate oscillators phase-locked using several phase-locked loops (PLLs) [12]. Our system demodulates the signal in the optical domain, so we create our carriers at optical frequencies with a mode-locked laser (MLL). A MLL is used since it creates multiple optical lines with a fixed spacing and mode-locking guarantees phase coherence between all of the lines, eliminating the need for multiple PLLs.

To maintain small size and compatibility with the rest of the silicon photonic receiver, our MLL, shown in Fig. 2(a), consists of a quantum-dash semiconductor optical amplifier (QD-SOA) [13] lens coupled to an external silicon photonic cavity [14]. Monolithic III/V on silicon mode-locked lasers have
shown good performance creating low-linewidth and narrowly spaced comb lines [15], [16] required for an RF-photonic link. While monolithic lasers have greater potential to offer low-cost manufacturing at large scales, we chose to use a lens-coupled design that allows us flexibility to change the mode-spacing by adjusting the lens spacing in the laser cavity.

A QD-SOA is an ideal gain material for mode-locked lasers due to its high gain and the ease to which it mode-locks. Our laser is hybrid-mode-locked with a combination of intrinsic passive four-wave mixing in the QD-SOA and the injection of an active locking RF frequency of 3GHz into the bias current of the QD-SOA. Active mode-locking precisely locks the comb spacing to the frequency separation of the transmitters’ RF carriers. In our system, this 3 GHz source is a shared frequency synthesizer, where in a real system the receiver circuit would need to incorporate a single PLL to lock the MLL comb separation to the carrier spacing of the received signal. Active mode-locking is also advantageous because it can reduce the RF beat-note frequency bandwidth from a passively-locked width of $\sim 15 \text{ kHz}$ to less than 10 Hz [17]. This is similar to conventional microwave oscillators and allows down-conversion of data from different carriers to correctly overlap at baseband without added phase-noise from the MLL.

The silicon cavity has a single intra-cavity ring filter that restricts the number of comb lines generated to a 50 GHz bandwidth. An integrated tunable mirror allows for the cavity Q to be actively tuned and a grating coupler provides a monitor output port.

To ensure the up-converted RF signal is frequency and phase locked to the optical LO, the MLL is injection locked to the external cavity laser used for up-conversion using a power tap and optical circulator as shown in Fig. 1. The intra-cavity ring filter of the MLL is then tuned to allow just a few comb lines to lase on the lower frequency side of the injected CW laser. The resultant output of the MLL, depicted in Fig. 2(b), has nine comb lines within a 3 dB bandwidth. The four comb lines that are 18 GHz, 15 GHz, 12 GHz, and 9 GHz away from the injected CW laser line are subsequently used to create the optical LO of the receiver.

IV. SILICON PHOTONICS PHASE ENCODER

The output of the MLL is amplified with an erbium-doped fiber-amplifier (EDFA) and then input to a four-channel silicon photonic phase encoder, pictured in Fig. 3 and shown schematically in Fig. 4(a). The phase encoder consists of four channels in parallel, each channel consisting of a 2nd order silicon racetrack-ring filter followed by a linear phase shifter. Eleven thermal phase shifters, each driven by a 12-bit digital-to-analog current supply, control the filter shape, frequency, and phase of the phase encoder. Each channel has two coupled rings that are independently tuned. When properly tuned to be completely overlapping, a single channel exhibits a 2 GHz bandwidth and can be tuned to any arbitrary frequency. This is 5x narrower than the best integrated spectral-phase encoder demonstrated previously [18], and allows for very closely spaced comb lines to be independently filtered. The phase shifter following each channel then allows the phase of the selected comb line to be tuned arbitrarily. By tuning the four channels to 3 GHz spacing, each channel can select a single MLL comb line and encode it with the desired optical phase.

The 2nd order coupled ring encoder was designed with a target 3 dB bandwidth of 2 GHz and a free spectral range (FSR) of 50 GHz. The filters were synthesized based on flat-top filter parameters. As a result, the coupling length and gaps of the coupled racetrack ring filter were designed to be 8.67 $\mu$m, 0.3 $\mu$m and 0.52 $\mu$m, respectively. The insertion loss of each coupled ring filter mainly comes from the propagation loss of the waveguide. To obtain an insertion loss lower than 0.5 dB, the waveguide propagation loss has to be lower than 0.2 dB/cm from our simulations. Therefore, the waveguide was tapered up to 2.5 $\mu$m for low propagation loss in the coupled ring filter. Each ring has a thermal phase shifter attached to it to ensure flexible tunability of the ring.

The utilized filter shape is shown in Fig. 4(b). The resultant output of the phase encoder, when the MLL spectrum in Fig. 4(c) is input, is shown in Fig. 4(d). Four comb lines, within 1 dB power of each other, are successfully selected, with neighboring comb lines suppressed by $>20$ dB. Once the thermal
tuning elements stabilize, no further tuning is required and the filter remains stable over extended periods of time (weeks). The global temperature of the silicon photonic chip is managed with an actively controlled thermo-electric cooler.

The phase encoder is capable of encoding arbitrary phases on the different comb lines in order to create arbitrary phase codes. Since four carriers are used, this system can generate up to four orthogonal codes, each of which could be simultaneously used by different RF users. The simplest phase code, 0000, is generated if all four carriers have the same phase. This code can easily be seen in the time domain if the four carriers are mixed together on a photodiode. The resultant output is an infinite train of pulses at 3 GHz, i.e., 333 ps separation as shown in Fig. 5(a). If the second and fourth comb lines are shifted by $\pi$ radians, then the resultant code 0101 is generated as shown in Fig. 5(c). The final two orthogonal codes, 0011 and 0110, are shown in Fig. 5(b), (d). Time-domain waveforms of all code combinations match well with their theoretically predicted shapes confirming good phase encoding from the silicon photonic chip. The small discrepancy in amplitude of some peaks comes from small amplitude variations between the four optical comb lines.

The time-domain waveforms of the four orthogonal codes reveal one of the difficulties with CDMA coding, which is code timing synchronization. The four codes are only truly orthogonal when they are temporally aligned. For example, code 0101 is a time-shifted version of code 0000. In electronic-based CDMA, this temporal alignment is done in the electrical domain. Since we are using an optical CDMA correlator, we must do temporal alignment of the incoming signal and optical LO in the optical domain. This requires precise optical path-length matching between transmitter and optical LO much shorter than the repetition rate of the code, $<300$ ps. In a non-stationary system, this will require either a tunable delay element on the incoming RF signal, a tunable optical delay line, or timing control of the MLL from which the optical LO is generated. One way to mitigate this timing requirement is to use more carriers, and therefore use closer spaced carriers, since the code repletion rate is equal to the carrier spacing.

V. SYSTEM MEASUREMENT RESULTS

The full system was first tested at a baud rate of 1.4 GHz. The RF and then optical frequency spectrum at different stages of the system is depicted in Fig. 6. The transmitted spectrum shows a very clean BPSK signal with well suppressed carriers and no overlap between primary lobes of the modulated signal between different carriers. The received signal is highly distorted, with several narrow frequency regions of significant power loss most likely caused by multi-path interference. The system is tested in a crowded optical lab and therefore is expected to suffer from a significant amount of fading. Fig. 7(a) shows the correlated baseband data (red) measured on a single photodiode with integrated trans-impedance amplifier and low-pass filtered with a 1 GHz RF filter. As shown in the black curve of Fig. 7(a), the original bit sequence (green) can be successfully recovered by thresholding the correlated baseband data. However, slow optical phase rotations between the optical LO and the received data causes the correlated baseband data to rotate between in-phase (I) and quadrature (Q) components. Since only one component can be measured with a balanced diode, the signal is completely lost for large periods of time. To correct for this, a $90^\circ$ optical hybrid and two diodes must be used to simultaneous measure the I and Q components.

Next, the system was tested with a 3 GHz BPSK signal, which is equal to the RF carrier spacing. This fully spreads the data out over the 12 GHz instantaneous bandwidth and creates a very flat hyper-wideband power spectrum, shown in Fig. 6(e). A $90^\circ$ optical hybrid and two 12 GHz photo-receivers were used to detect the correlated baseband signal so that the full quadrature signal could be captured and then low-speed (3 GHz) digital signal processing was used to analyze the data. Note that much lower bandwidth photo-receivers would have produced similar results, but were not available during testing. The output of the photo-receivers was filtered with a 2 GHz low-pass RF filter.

At a received RF power of $-35$ dBm and a data rate of 3Gbps, the transmitted data was successfully recovered error-free with an error vector magnitude (EVM) of 18.8%. This...
shows the robustness of the hyper-wideband link even in the presence of significant multi-path interference induced channel fading. Next, a narrowband interferer was introduced to test the jamming resistance of the broadband signal. Received signal EVM versus interference power and frequency offset from a signal RF carrier frequency is shown in Fig. 8. Received EVM versus jammer offset frequency is not constant due to different artifacts introduced on the baseband correlated signal as well as varying channel fading experienced at different RF frequencies. By utilizing an electronic repetition code, the received signal quality can be further increased in the presence of a narrowband interferer. With an interferer power 5 dB greater than the hyper-wideband signal, 8x averaging of the signal can reduce the EVM from 37.2% to less than 20%, which is error free. When the interferer was increased to −25 dBm, 10 dB above signal power, averaging increased the received signal EVM to 35.8%.

VI. INTEGRATED NOTCH FILTERS

Further jam resistance can be achieved by filtering out narrowband jamming signals with the integrated notch filter bank. In the silicon photonic receiver, five silicon ring notch filters were placed in series. The notch filters were designed to have a 3dB bandwidth of 1 GHz, and an FSR of 500 GHz. To achieve the largest extinction possible (critical coupling), the correct spacing between the waveguide and ring resonator must be achieved. The ideal waveguide-ring spacing was simulated to be 380 nm. To account for the fabrication variations, each ring filter had a slightly different waveguide-ring spacing so that regardless of fabrication variability one ring would have optimum coupling. Furthermore, multiple ring filters can be thermally tuned to overlap in spectrum, increasing the extinction ratio of the notch filter at the wavelength of interest. The notch filter array is shown in Fig. 9(a).
The five notch filters were measured and the two with the best coupling are shown in Fig. 9(b). These two notch filters detuned from each other, achieved extinction ratios of 21 dB and 14 dB respectively with bandwidths of 2 GHz. When the two are tuned to the same wavelength the net extinction ratio becomes 33 dB, while the bandwidth increases to 4 GHz. The bandwidth is measured at the 3 dB value from zero attenuation. The two can be simultaneously tuned together to adjust the notched frequency. Tuning over 9 GHz is shown in Fig. 9(c), although there is no upper bound to how far the rings can tune.

Finally, the notch filters were used to reject an unwanted interference signal in the full system testbed. Fig. 10 shows the optical spectrum of a received 3Gbps BPSK signal spread over four RF carriers with a single large amplitude jamming signal towards the center of the bandwidth. When the notch filters are tuned into place, the jamming signal can be reduced by up to 27 dB. Jamming reduction (27 dB) is slightly less than the extinction ratio of the two rings (33 dB) due to polarization rotation effects on-chip that rotate part of the signal into the TM polarization that cannot be filtered by the notch filters. In future iterations, this effect can be eliminated by filtering out all TM light on-chip.

When the maximum extinction ratio is achieved, the two ring filters also filter out a complete channel of the received spectrum. Due to the hyper-wideband spreading, this is only a minor 1.25 dB loss in total signal power. Using a low-loss material such as silicon nitride for the ring filter would allow even narrower-bandwidth notch filters resulting in even less signal loss. Such devices have exhibited high extinction ratios with bandwidths as low as 250 MHz [19].

VII. DISCUSSION AND CONCLUSION

We have demonstrated for the first time a hyper-wideband wireless RF system enabled by an integrated optoelectronic platform. Leveraging the wide bandwidth of optics, our system features a four-channel CDMA receiver with an instantaneous bandwidth greater than 85% of the center frequency of 14 GHz. To the best of our knowledge, there has never been a demonstration of an equivalent system using a traditional RF receiver architecture. Optical coherent heterodyne is used to optically process the received RF signal to a baseband signal, allowing the 12 GHz of instantaneous bandwidth to be received with electronics bandwidth of only 3 GHz.

One of the biggest advantages of our approach is the ease of scalability to larger carrier numbers and wider bandwidths. By using a MLL followed by a silicon phase encoder, our system can add more carriers and utilize a wider bandwidth by simply adding more channels to the encoder. A traditional RF approach would require additional PLLs, oscillators, mixers, and an ever increasingly complex filter network for every additional channel added. Integrated MLLs with mode spacing down to 1 GHz have been demonstrated [16], which would allow our system to not only add more carriers but also reduce the channel spacing to increase the number of CDMA channels with minimal system changes.

The main limitation to the bandwidth achievable in our system is the speed of the low-noise amplifier and optical modulator that upconverts the RF signal to the optical domain. However, recent advances in high-speed hybridized silicon photonics systems have demonstrated electrical control, optical circuits, and RF circuits integrated onto a single chip with driver and modulator bandwidths in excess of 30 GHz [20]. This suggests future silicon photonics based hyper-wideband systems could achieve even greater instantaneous bandwidths all in a chip-scale package.

Finally, an optical approach allows us to obtain 27 dB of narrowband interference rejection tunable over the entire 12 GHz instantaneous bandwidth using silicon ring drop filters. Such a large rejection ratio tunable over such a large bandwidth would require bulky mechanical filters if implemented in the electrical domain. By utilizing lower-loss materials such as silicon ni-
tride, these optical filters could be even narrower in bandwidth allowing for lower signal loss and for large banks of drop filters to be implemented in case multiple interference signals are present.

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REFERENCES


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