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Hyper-Wideband Wireless Communication Link Empowered by Silicon Photonics for Low Cast RF Systems

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***Abstract*— The first silicon photonics empoweredhyper-wideband wireless link with an instantaneous bandwidth of 12 GHz, which is 85% of the center frequency of 14 GHz. The silicon photonics based RF receiver involves of a four-channel optical phase encoder, an integrated hybrid-silicon mode-locked laser, and two silicon ring notch filters. The received CDMA RF wireless signal is interrelated to baseband using coherent optical heterodyne at a data rate of 3 Gbps error-free with electronics bandwidth of only 3 GHz. Hyper-wideband RF transmission allows for data complication and increased jamming resistance from narrowband interferers. The narrowband silicon photonic ring filters allow for further interference rejection of greater than 27 dB tunable over the full 20 GHz of RF spectrum.**

***Index Terms*—Silicon microwave photonics, hyper-widebandRF, data obfuscation, spread-spectrum.**

I. Introduction

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. Conversely, ultra-wideband RF systems use a very low spectral power density signal spread over a very large instantaneous RF spectral bandwidth (>500 MHz). The low spectral power density of these systems can be used to obfuscate data transmission and prevent interference with other signals while their ultra-wide bandwidth is capable of supporting multiple users through code division multiplexing (CMDA) and can be designed to be highly jam resistant through large processing gain [1]. To increase data rates and processing gain, ever larger RF bandwidth is required. Hyper-wideband systems are defined as wideband RF systems that occupy an instantaneous bandwidth >10 GHz [2]. These systems are very complex and costly to implement as they require high-speed electronics (>10 GHz) and suffer from poor tunable filters required to re-ject unwanted narrowband interference.

Silicon microwave photonics offers an integrated optoelectronic platform that can be used to generate and manipulate RF signals in the optical domain [3]. Through the use of a comb

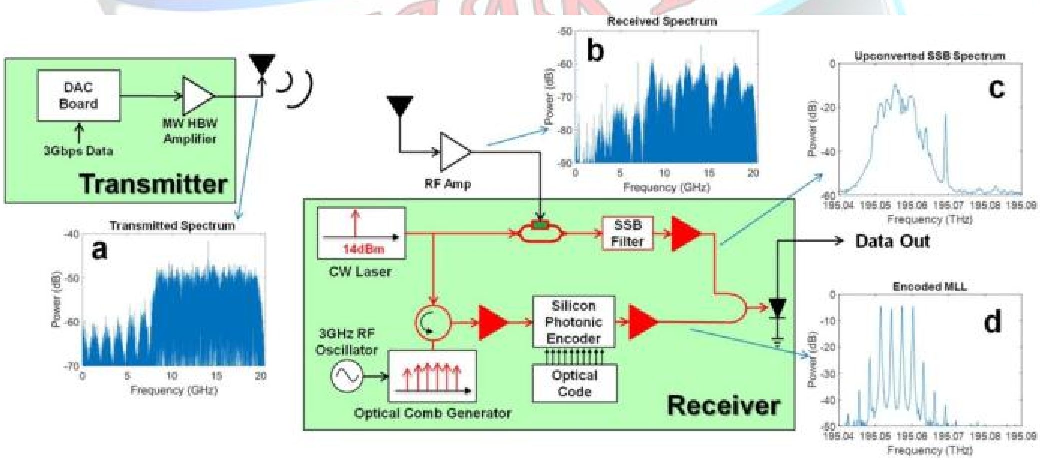

Fig. 1. Schematic diagram of Silicon Photonic RF Link. (a) Transmitted RF spectrum from transmitter. (b) Received RF spectrum from receive antenna. (c) RF signal up-converted to optical frequency and single sideband filtered. (d) Phase-encoded optical comb local oscillator.

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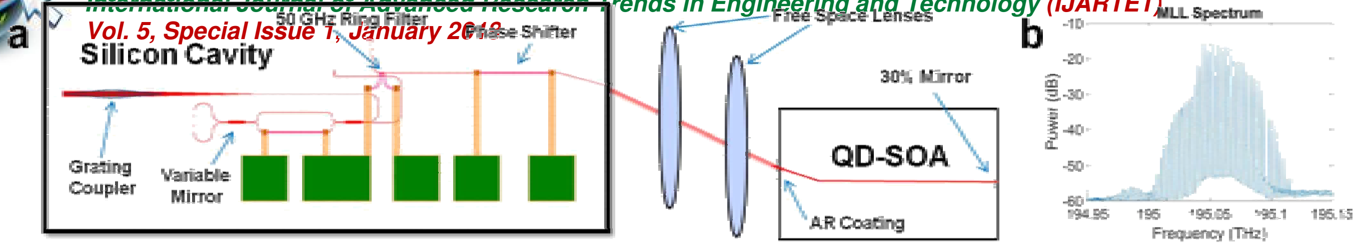

Fig. 2. (a) Hybrid Si-III/V Mode-Locked Laser. (b) Output lasing spectrum of MLL.

laser source, multiple RF carriers can be simultaneously generated without the need for high-speed electronics and narrow bandwidth silicon based filters allow individual carriers to be independently addressed and modulated. In addition, silicon photonics offers bandpass and bandstop filtering with unparalleled tunability (>1 THz) that allows for narrowband filtering [4] of unwanted signals that is not possible in the electrical domain.

In this paper we present for the first time a hyper-wideband wireless RF system based on an integrated silicon-photonics platform that uses 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 3 Gbaud over a wireless link.

II. System Overview

the wrong phase code is used for the LO, the baseband coverted data destructively interferes leaving no signal on the out-put. Since four carriers are used, this system can simultaneously support up to four users using orthogonal codes.

The LO is phase encoded by filtering the output of a mode-locked laser (MLL) with a four-channel silicon photonic phase encoder. The MLL, shown in Fig. 2(a), consists of a quantum-dash semiconductor optical amplifier (QD-SOA) [6] coupled to an external silicon photonic cavity [7] with two free-space lenses. The silicon cavity has a single intra-cavity ring filter that restricts the number of comb lines generated to a 50 GHz band-width. An integrated tunable mirror allows for the cavity Q to be actively tuned and a grating coupler provides a monitor out-put port. The MLL mode spacing is actively locked with a 3 GHz RF signal injected into the QD-SOA and the MLL is opti-cally injection locked to the CW laser to ensure coherence be-tween the two light sources.

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The concept of the full system is shown in Fig. 1. In this work, we experimentally demonstrate a four-channel wireless link spanning from 8 GHz to 20 GHz with 3 GHz spacing. The transmitter consists of a high-speed arbitrary waveform generator (AWG), followed by a high-power RF amplifier and a pla-nar ultra-wideband antenna as described in [5]. The frequency range used was determined in order to match the operational bandwidth of the ultra-wideband antenna. The AWG produces the phase encoded RF signal consisting of four carriers modu-lated with the same 3 Gbps BPSK signal. Each carrier is given a phase offset from neighboring carriers corresponding to the CDMA phase code being employed.

The receiver consists of another planar ultra-wideband an-tenna followed by a low-noise amplifier which drives a lithium niobate Mach-Zenhder modulator. The modulator up-converts the RF signal onto a 1536 nm CW optical carrier. This up-con-version 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 as shown in Fig. 1(c). The resultant signal is then beat against a local oscillator (LO) consisting of four phase-encoded comb lines frequency matched to the carrier frequencies of the up-converted RF sig-nal. If the relative phase encoded on the LO comb lines matches the relative phase encoded on the corresponding RF carrier fre-quencies, the data is constructively correlated to baseband. If

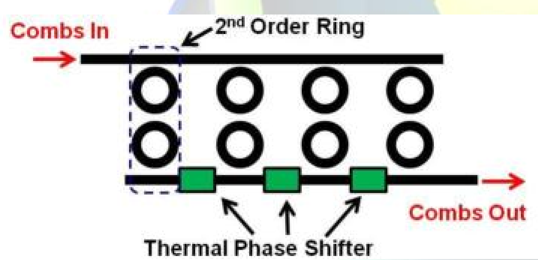

Fig. 3. Silicon photonic phase encoder consisting of four 2nd order ring fil-ters followed by thermal phase shifters.

The output of the MLL, shown in Fig. 2(b), is amplified with an EDFA and then input into the silicon phase encoder, shown schematically in Fig. 3. The phase encoder consists of four channels in parallel, each channel consisting of a second order silicon ring filter followed by a thermal phase shifter. The opti-cal phase encoder is realized in silicon photonics using a similar approach as demonstrated previously in PLC technology [8]. Each channel exhibits a 2 GHz bandwidth and can be tuned to an arbitrary frequency. This is 5x narrower than the best inte-grated spectral-phase encoder demonstrated previously [8], and allows for very closely spaced comb lines to be independently tuned. By tuning the four channels to 3 GHz spacing, each channel can select a single MLL comb line and encode it with any arbitrary desired optical phase relative to neighboring comb lines.

III. System Measurement Results

The full system was tested at a baud rate of 3 GHz, which matched the carrier spacing of the RF data. This results in a very flat spectrum, as shown in Fig. 1(a). The received and optically correlated signal was detected on two 12 GHz photodiodes with integrated trans-impedance amplifiers. Fig. 4 shows the corre-lated baseband data (red) obtained on just one photodiode and low-pass filtered with a 2 GHz RF filter. As shown in the black curve of Fig. 4, the original bit sequence (green) can be recov-ered by thresholding the correlated baseband data. However, slow optical phase rotations between the MLL LO and the re-ceived data causes the correlated baseband data to rotate be-tween in-phase and quadrature components. Therefore, two photo-receivers were used so that the full quadrature signal could be captured and then digital signal processing was used to analyze the data. At a received RF power of -35 dBm the transmitted data was successfully recovered error-free with a Q-factor of 28.4.

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to -25 dBm signal averaging was able to increase the received signal Q to ~8.

Further jam resistance can be achieved by filtering out the jamming signal with integrated notch filters. The notch filters consist of a single silicon-ring filter with 2 GHz bandwidth and 20 dB rejection per ring. Fig. 6 shows the up-converted RF data with a large amplitude jamming signal and the same signal with the jammer attenuated with two ring drop filters. Up to 27 dB of jammer attenuation is achieved while sacrificing only a sin-gle received channel.

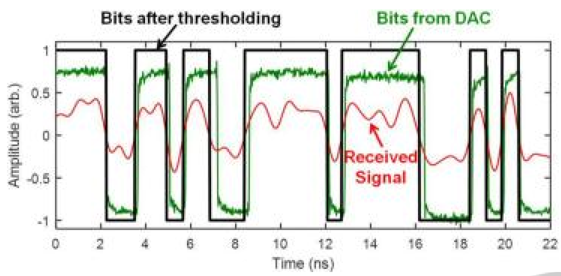

Fig. 4. Low-pass filtered correlated baseband signal (red), recovered bits (black), and transmitted data (green).

Next, an interferer was introduced to test the jamming re-sistance of the broadband signal. Received signal Q versus in-terference power and frequency offset from a signal RF carrier frequency is shown in Fig. 5 with the received signal power fixed at -35 dBm. By utilizing an electronic repetition code, the signal Q can be further increased to error free with 8x averaging at -30 dBm interferer power. When the interferer was increased

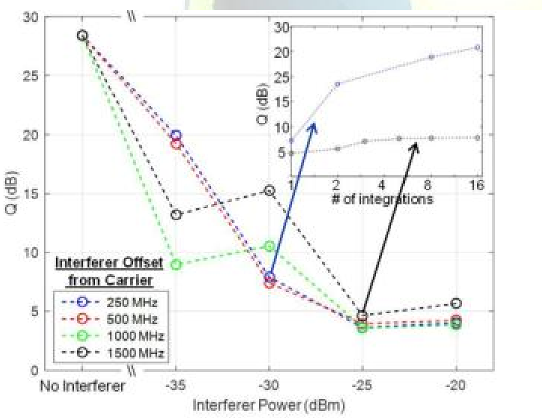

Fig. 5. Received signal Q-factor versus jamming signal power and jammer offset from signal carrier for a received data power of -35dBm.

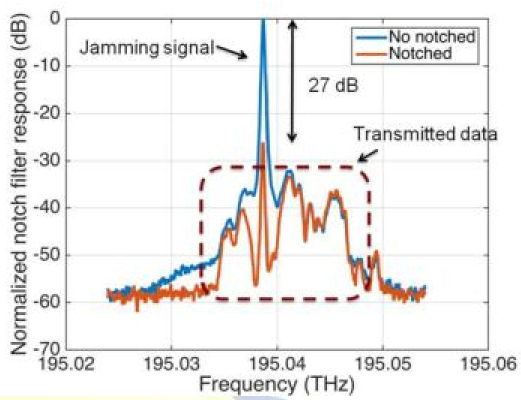

Fig. 6. (blue) Up-converted RF data with larger jamming signal. (red) Same data after two silicon drop filters have been tuned to attenuate the jammer.

IV. Conclusion

We have demonstrated for the first time a hyper-wideband wireless RF system enabled by an integrated silicon photonic MLL, a four-channel phase encoder, and a notch filter. Lever-aging the wide bandwidth of optics, our system features an in-stantaneous bandwidth greater than 85% of the center frequency. 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. The four subcarrier system is capable of supporting up to four simultaneous users. In addition, 27 dB of jammer rejection is demonstrated with integrated silicon ring drop filters. Such a system is an ideal platform for low-cost RF systems where a hyper-wideband signal is required for data obfuscation and interference rejection.

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