SAND2018-1357C

Photonic Integrated Circuits for RF Electronic Systems

Andrew Stark, Benjamin Yang, Chris Ward, Kyle Davis, Tim Brothers, Brent Wagner
Georgia Tech Research Institute
Atlanta USA
andy.stark@gtri.gatech.edu

Jerrod Langston, Christian Bottenfield, Gareeyasee Saha, Justin Lavrencik, Stephen E. Ralph
Georgia Institute of Technology
Atlanta USA

Arthur Paollela, Charles Middleton, Richard DeSalvo
Harris Corporation
Melbourne USA

Michael Gehl, Chris DeRose, Anthony Lentine
Sandia National Lab
Albuquerque USA

***Abstract*—We summarize several years of work to apply photonics to RF electronics systems via analog remoting, frequency conversion, and channelization. High-performance discrete component system (DCS) demonstrators have been constructed. Efforts are underway to further reduce size, weight, and power (SWaP) with photonic integrated circuit technology.**

***Keywords*—RF photonics; photonic integrated circuits; RF systems; frequency conversion; channelization**

I. RF Electronic Systems

Photonics technologies can provide many advantages to radio frequency (RF) systems: low, frequency-independent loss, large bandwidth; reduced size, weight and power (SWaP); electro-magnetic interference (EMI) immunity; and novel functions. RF photonic research is typically presented in terms of raw performance and with limited context. This "RF black box" approach obfuscates key design space trades necessary to meaningfully realize system level improvements enabled by photonics. This article is intended to present photonics from an RF system design perspective that includes not only the photonic but the RF and digital systems. As such, photonic designs for a set of common RF building-block architectures are presented across a larger design space. Some trade-offs for traditional RF design are explained as they are contrasted against and complemented by photonic design options.

GTRI, GT-ECE, Harris Corp, and Sandia National Labs have collaborated to develop photonics technology specifically for insertion into large wideband RF systems. Here we describe three functions for RF systems implemented in discrete component photonics: (1) analog remoting, (2) frequency conversion, and (3) channelization. For each we have also launched efforts to miniaturize the technology by fabricating photonic integrated circuits (PICs) to transition to ultra-low SWaP systems

II. Photonics For RF Electronic Systems

A typical RF electronic system transmits and receives multiple RF signals from many antennas. These RF signals may be comprised of communication, radar, or other waveforms. While the signal performance requirements are different between communication, radar, and other RF systems, the functional requirements are nearly identical. These systems must receive a complex waveform, transport the waveform to a specific location, switch it properly, convert the received RF to an intermediate frequency (IF), digitize, apply digital signal processing, convert back to an analog signal, up-convert, switch, transport, and finally transmit, Figure 1. Legacy systems may employ analog processing at IF in place of digital processing.

On larger platforms (e.g. aircraft), these signals are routed to a central equipment bay for processing and then re-distributed back to the antenna for transmission. The processing hardware, antennas, amplifiers, and cabling for the disparate signals may or may not be shared between the disparate sub-systems. The design constraints for aerial platforms are typically specified to achieve the required RF performance while minimizing SWaP and meeting environmental specifications.

RF electronic system performance is often driven by the capability of the digitizers: conversion rate, dynamic range, and bandwidth. Modern ADCs exhibit ~4 GS/s, 8-9 ENOB, with a few GHz of analog BW[1][2]. Modern DACs exhibit >4 GS/s, 8-9 ENOB, and >5 GHz of analog BW [3].

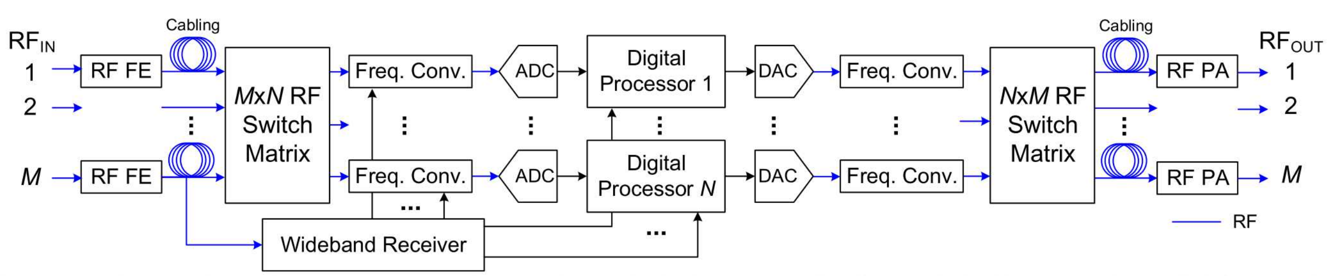


Figure 1. Modern RF electronic systems. In general, M number of physical antennas or bands are switched into N number of digital processing elements. A wideband receiver subsystem is often employed to guide frequency conversion and digital processors since the instantaneous bandwidth (IBW) of digitizers is limited.

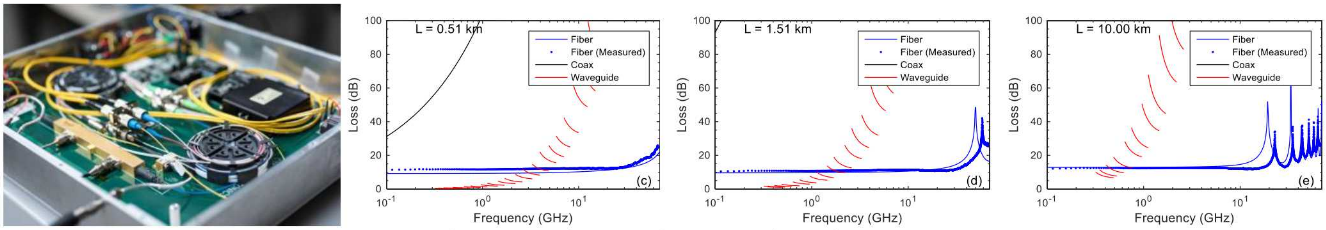


Figure 2. Analog remoting DCS gain performance.

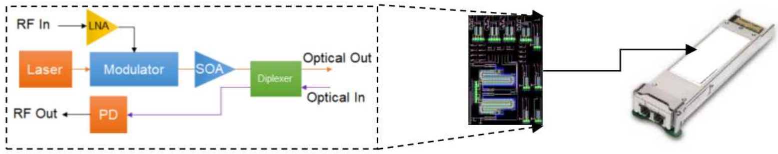


Figure 3. Analog remoting concept. The block diagram is simply an example of how PICs could be used in order to achieve telecom-style form factors for analog transceivers and does not represent a selected architecture. This dramatic SWaP reduction would enable more ready adoption across RF systems.

II.A. Analog Remoting

Analog remoting is the most direct translation of photonic technology from telecommunications to RF electronic systems. Remoting leverages the low-loss and EMI-immunity characteristics of fiber optics along with high-BW photonic components to transport signals from one physical location to another. Analog signal transport via fiber is well-understood [1] and employed extensively by the telecom industry in RF over glass (RFoG) systems. In a more general sense, RF-over-fiber (RFoF) systems offer clear advantages in performance for RF signal distribution, especially for signals above the typical 2-18 GHz bands. This performance advantage is readily quantifiable for COTS parts, and some semi-integrated systems. GTRI has constructed a pair of DCS demonstrators for 40 GHz remoting, Figure 2. While seemingly mundane, wideband remoting has experienced increased performance and deployments proven to be an integral part of the photonics value proposition. The DCS remoting link demonstrates superior performance when compared to traditional coaxial cabling and metal waveguides for frequencies above a few hundred MHz and distances beyond a few hundred meters, even with dispersive fading at high frequencies. Numerous example of analog remoting links exist on the market today, e.g. [5][6].

The commercial industry leverages volume production to reduce cost of digital fiber transceivers. For example, 2.5 Gb/s transceivers are available commercially for a few dollars and 10 Gb/s transceivers are available for less than $100. These transceiver modules are produced in volumes of 10s of millions, burn a few watts, can be less than 1 in^3 (e.g. small form pluggable – SFP), can support link distances of up to 80 km, and are generally engineered against particular specifications. While research in RFoF is well-developed, engineering investment has significantly trailed that of digital fiber systems.

Photonic integrated circuits are now commercially available for digital telecom applications including so-called digital coherent receivers capable of receiving a variety of QAM modulation formats and baud rates as high as 32 GHz. These subsystems exhibit essentially identical *system-level* performance as the discrete optical components they replace. Thus PICs have the potential to shrink the required remoting hardware to SFP-style packages further increasing deployment opportunities. Analog PICs are still in the concept stage at GT, Figure 2.

Although there are many similarities between analog and digital optical systems, analog signal generation, transport, processing, and detections requires advances in both electronics and optics to fully realize the potential of integrated optics. For example, the link performance of a wideband RFoF link depends directly on the received power. Therefore, PICs capable of handling and launching higher optical power are beneficial. Furthermore, high dynamic range requires highly linear modulation and detection. These requirements are managed by extensive digital signal process in the telecom space, however there is not the equivalent analog signal processing technology currently available. Efforts to combine highly functional analog circuits together with photonic integrated circuits either monolithically or as part of a multi-chip module are the focus of our team's strategic plan.

Additionally, engineering the packaging and components to support the demanding mechanical and vibrational environments that RF systems operate in will be critical for the success of fiber remoting systems.

II.B. Frequency Conversion

Frequency conversion describes the process of receiving one RF frequency band and shifting it to another (usually lower) intermediate frequency (IF) for digitization and/or processing. After processing, the frequency converter must also translate the signal back to RF for transmission. Harris Corp has previously demonstrated a photonic downconversion technology [7]. A full transceiver (down and up) was constructed from COTS and demonstrated in [8].

The photonic frequency transceiver works in the following manner. A single laser is optically amplified. The amplified laser carrier is then split three ways. On one path, a null-biased MZM modulates an IF signal onto the laser carrier. The lower sideband of the IF signal is selected by a tunable filter, throwing away most of the carrier power. On the second path, a phase modulator receives a local oscillator (LO) signal. The upper sideband of the LO is selected by another tunable filter. This

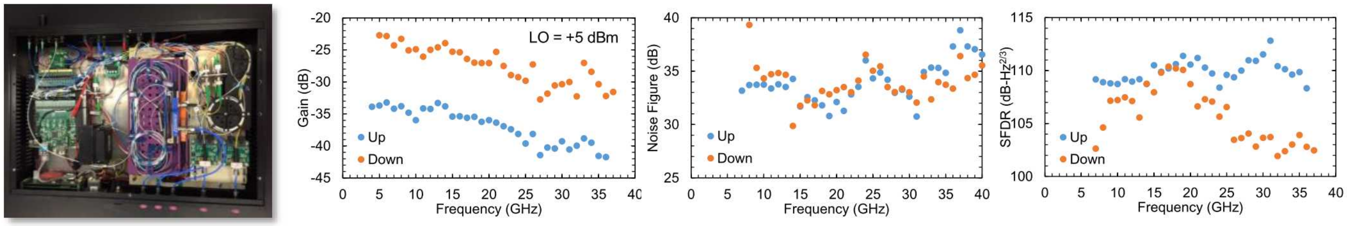


Figure 4. Gain, noise figure, and SFDR of the photonic frequency conversion DCS. RF gain can be increased in a 1:1 manner by increasing the input RF power of the LO signal.

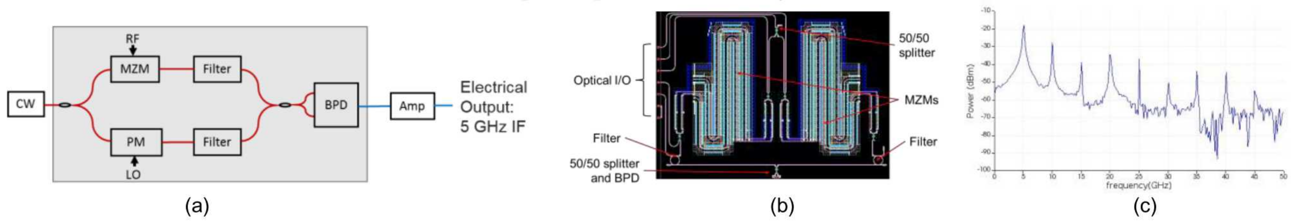


Figure 5. (a) Block diagram of an integrated downconverter using. (b) Layout of the downconverter PIC which was built into GlobalFoundaries SiPh process. (c) Simulated electrical output of an integrated downconverter for a 5 GHz IF.

signal is then power split and combined with the IF signal from the first path. The combined signal is detected via a photodiode where the square-law action converts the IF signal to an RF frequency that is the difference between the LO and IF frequencies. On the third path, a null-biased MZM receives the RF signal and a tunable filter selects the upper sideband. The sideband signal is then combined with the second half of the LO split. A balanced photodiode performs conversion to IF.

The photonic frequency transceiver system is capable of 4-40 GHz, 4 GHZ IBW, and 45-55 dB dynamic range in 1G BW, Figure 4. Full performance details of this DCS as well as demonstrations with a range of signal types are available in [8]-[10].

GT-ECE in collaboration with Harris has launched a project to design, fabricate and validate a PIC with all the functionality of the downconverter transceiver. A variety of foundries, including the AIM photonics manufacturing institute, are establishing a complete PIC infrastructure analogous to that of the electronics industry.

Lumerical INTERCONNECT simulations were performed to confirm the downconverter functionality and behavior in an integrated photonic environment, using parameters resembling current silicon photonic foundry capabilities. A block diagram of the downconverter is illustrated in Figure 5(a). An MZM with 5 dB insertion loss, 1 V·cm $V\pi L$, and 15 GHz bandwidth performs the electrical-optical conversion, while a phase modulator of similar bandwidth provides the reference local oscillator (LO). The RF and LO optical signals are filtered by 13 GHz ring resonator filters. The rings were designed via Lumerical DEVICE simulations. A balanced photodetector comprised of 25 GHz PINs with R = 0.85 A/W mixes the RF and LO signals, generating an IF output. Completed layout with all components labeled appears in Figure 5(b). Simulated 5GHz output is shown in Figure 5(c). The laser source assumed a RIN of -150 dB/Hz. This design was taped out into GlobalFoundries 9WG process and was received December 2017. They are actively under test.

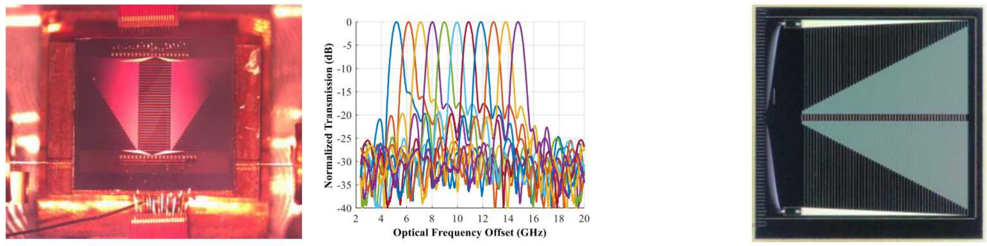
II.C. Channelization

Wideband channelization is another RF electronic sub-system. Channelized receivers are typically employed to provide continuous situational awareness and to enable dynamic allocation of available RF resources (detection, digitization and inspection) and thereby maximize sensitivity and signal intelligence.

GTRI has constructed a discrete component channelizer based on fiber Bragg Grating (FBG) filters and high-speed modulators (70G+).

GTRI has partnered with Sandia National Labs to leverage PICs and build an arrayed-waveguide grating (AWG) filter bank to dramatically reduce the SWaP of this channelized receiver. Figure 6 shows the fabricated Sandia National Laboratory 11-channel AWG along with the measured optical transmission (right). The device is a silicon PIC with 35 integrated waveguides and phase shifters achieving a 600 MHz 3-dB bandwidth with a total area of 1.1 cm^2. Initial demonstrations of AWGs for RF channelization have shown 1 GHz bins Figure 6(b) [11]. GTRI received the next version of the AWG PICs Jan 2018, Figure 6(c). This device comprises 20 channels of 2 GHz bins with a PD at the output of each waveguide. This device is still under test.

The AWG chip can be used in many architectures as an RF receiver. If a standard RF Photonic link is employed, the AWG will function directly as a "power-in-the-bucket" channelizer. The RF envelope may be extracted with a simple photodiode device connected to the output of each waveguide. Therefore, the photodiode's speed can be set by the RF-envelope modulation rate desired for a given channel—in most cases 1 GHz is more than sufficient. If an RF-LO block is included then RF down conversion is possible by generating a phase coherent continuous-wave (CW) sideband offset by the desired intermediate frequency (IF). For example, an optical CW tone offset from the carrier frequency by 15 GHz would down-convert a 16 GHz optical RF sideband to an IF of 1 GHz. In this case, the photo-diode speed is only required to be as fast as the desired IF center frequency plus the upper bandwidth of the



(a) (b) (c)

Figure 6. (a) Silicon photonic AWG constructed by Sandia NL. (b) Filter performance of the AWG in (a) exhibiting approximately 600 MHz of 3 dB BW, ~20 dB of optical isolation, and 11 channels. (c) New version of the AWG with 40, ~2 GHz channels.

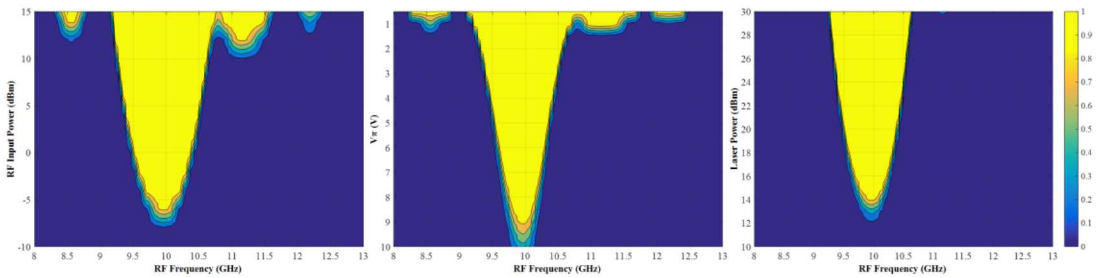


Figure 7. Probability of detection contour plots for one AWG channel centered at 10 GHz as a function of RF input power (left), Vπ (middle), and laser power (right).

channel required. Section II.B describes photonic frequency conversion in detail.

A full RF-envelope detection model was developed to assess RF receiver system performance of this channelized receiver. The measured performance of the AWG, Figure 6(b), was incorporated into the model. The MZM was null-biased to suppress the optical carrier before the AWG. The signal-to-noise ratio (SNR) is determined by the ratio of RF-envelope photo-current to the photo-current noise. Photo-diode noise current was modeled as a combination of shot, thermal, and RIN according to standard conventions. For RF receiver systems probability of detection is a key performance specification (analogous to BER for communication systems). The probability of detection, P_D, can be determined using the Albersheim equations [13]. For our model the number of incoherently integrated pulses was set to *N=1*.

Figure 7 shows the modeled P_D contours of the envelope detection system through one channel of the AWG for an input tone centered at 10 GHz.

In the first simulation, RF input power was varied and the optical system has the following parameters: $P_{laser} = 20\ dBm$, $V_\pi = 4.5\ V$, $\alpha_{MZM} = 4\ dB$, $R = 0.9\ A/W$, $BW_{PD} = 1\ GHz$, an AWG insertion loss of 10 dB (average loss of fabricated device), and $RIN = -160\ dBc/Hz$ (readily available in 100 mW commercial lasers). Results are shown in the left panel of Figure 7. $P_D = 1$ follows the filter shape and measurement accuracy of the device from -10 dBm to approx. +10 dBm RF input powers. As the power increases, higher frequencies creep into the receiver processor according to the filter isloation of the AWG.

We then fixed the RF input power at 0 dBm and scanned modulator Vπ from 1 to 10 Volts (using the same other optical parameters), Figure 7 (middle). Increasing Vπ has the effect of constricting the $P_D = 1$ detection width of the system; a super-low Vπ=1V device would introduce harmonics even at +0dBm input RF power because the system dynamic range is limited by the filter performance of the AWG.

If instead the laser power is scanned, Figure 7 (right), a similar system response is demonstrated: the $P_D = 1$ detection width widens for higher power. Lower Vπ and/or higher laser power result in lower system noise figure, increasing detection width. The system model shows good channel isolation while achieving the SNR needed for near 100% probability of detection

III. Conclusions

We have summarized years of effort to exploity photonics technology to improve various attributes of RF electronics systems use for analog remoting, frequency conversion, and channelization. High-performance DCS demonstrators have been constructed at relatively high technology readiness level (TRL). Efforts are underway to further SWaP-reduce with photonic integrated circuit technology.

Acknowledgment

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

The authors thank GTRI, GT-ECE, Sandia, and Harris Corp for their support of this week.

References

[1] http://www.ti.com/product/adc12d1800, accessed 11 Jan 2018.

[2] http://www.ti.com/product/adc12j4000, accessed 11 Jan 2018.

[3] http://www.e2v.com/products/ev12ds400a/, accessed 11 Jan 2018

[4] V. J. Urick et al., "Long-Haul Analog Photonics," in Journal of Lightwave Technology, vol. 29, no. 8, pp. 1182-1205, April15, 2011.

[5] http://www.pharad.com/rf-over-fiber.html, accessed 11 Jan 2018.

[6] http://linphotonics.com/products/, accessed 11 Jan 2018.

[7] A. Mast, C. Middleton, S. Meredith, and R. DeSalvo, “Extending Frequency and Bandwidth Through the Use of Agile, High Dynamic Range Photonic Converters,” IEEE Aerospace Conference, 2012.

[8] A. J. Stark, M. D. Merritt, J. Langston, C. Middleton, R. DeSalvo and S. E. Ralph, "Photonic frequency conversion for dynamic spectral access and signal remoting," 2016 IEEE Photonics Conference (IPC), Waikoloa, HI, 2016, pp. 279-280.

[9] J. Langston, M. D. Merrit, A. J. Stark, R. DeSalvo and S. E. Ralph, "Cyclostationarity-based classification of OFDM waveforms over photonic-assisted wireless links," 2016 IEEE Avionics and Vehicle Fiber-Optics and Photonics Conference (AVFOP), Long Beach, CA, 2016, pp. 199-200. doi: 10.1109/AVFOP.2016.7789934

[10] S. Hughes, J. Langston, R. DeSalvo, C. Middleton, E. Grafer, S. E. Ralph, and A. Stark, "Agile Micro- and Millimeter-Wave Communication Using Photonic Frequency Conversion," in Optical Fiber Communication Conference, OSA Technical Digest (online) (Optical Society of America, 2016), paper W1G.5

[11] M. Gehl, D. Trotter, A. Starbuck, A. Pomerene, A. L. Lentine, and C. DeRose, "Active phase correction of high resolution silicon photonic arrayed waveguide gratings," Opt. Express 25, 6320-6334 (2017).

[12] http://www.aimphotonics.com/

[13] M. A. Richards, *Fundamentals of Radar Signal Processing*, second edition. McGraw-Hill, 2014