AFRL-RY-WP-TR-2017-0172

SIGNAL PROCESSING UTILIZING RADIO FREQUENCY PHOTONICS

Preetpaul S. Devgan

RF/EO Subsystems Branch
Aerospace Components & Subsystems Division

SEPTEMBER 2017
Final Report

Approved for public release; distribution is unlimited.

See additional restrictions described on inside pages

STINFO COPY

AIR FORCE RESEARCH LABORATORY
SENSORS DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7320
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

NOTICE AND SIGNATURE PAGE

This report was cleared for public release by the USAF 88th Air Base Wing (88 ABW) Public Affairs Office (PAO) and is available to the general public, including foreign nationals. Copies may be obtained from the Defense Technical Information Center (DTIC) (http://www.dtic.mil).

AFRL-RY-WP-TR-2017-0172 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

*//Signature//

PREETPAUL S. DEVGAN, Program manager
RF/EO Subsystems Branch
Aerospace Component & Subsystems Division

*//Signature//

TIMOTHY R. JOHNSON
Chief
RF/EO Subsystems Branch
Aerospace Component & Subsystems Division

*Disseminated copies will show “//Signature//” stamped or typed above the signature blocks.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE ***(DD-MM-YY)*** September 2017	**2. REPORT TYPE** Final	**3. DATES COVERED** ***(From - To)*** March 1, 2007 – August 31, 2017

4. TITLE AND SUBTITLE SIGNAL PROCESSING UTILIZING RADIO FREQUENCY PHOTONICS	**5a. CONTRACT NUMBER** In-house **5b. GRANT NUMBER** N/A **5c. PROGRAM ELEMENT NUMBER** N/A
6. AUTHOR(S) Preetpaul S. Devgan	**5d. PROJECT NUMBER** N/A **5e. TASK NUMBER** N/A **5f. WORK UNIT NUMBER** N/A
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) RF/EO Subsystems Branch, (AFRL/RYDR) Aerospace Components & Subsystems Division Air Force Research Laboratory, Sensors Directorate Wright-Patterson Air Force Base, OH 45433-7320 Air Force Materiel Command, United States Air Force	**8. PERFORMING ORGANIZATION REPORT NUMBER** AFRL-RY-WP-TR-2017-0172
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory Sensors Directorate Wright-Patterson Air Force Base, OH 45433-7320 Air Force Materiel Command United States Air Force	**10. SPONSORING/MONITORING AGENCY ACRONYM(S)** AFRL/RYDR **11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)** AFRL-RY-WP-TR-2017-0172

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

The U.S. Government is joint author of the work and has the right to use, modify, reproduce, release, perform, display or disclose the work. PAO case number 88ABW-2017-4239, Clearance Date 1 September 2017. Report contains color.

14. ABSTRACT

Radio Frequency (RF) photonics can be used for multiple signal processing applications. Down conversion, oscillators analog to digital conversion and waveform generation are examples of these. A review of the different photonic systems is described in this report.

15. SUBJECT TERMS

radio frequency, photonics, processing

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT:**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** (Monitor)
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Preetpaul S. Devgan
Unclassified	Unclassified	Unclassified	SAR	17	**19b. TELEPHONE NUMBER** *(Include Area Code)* N/A

Table of Contents

Section **Page**

List of Figures

Figure **Page**

1. INTRODUCTION

Often signal processing takes place in the digital domain. There is still a need for analog signal processing. These systems are used to prepare signals for digital analysis. Examples include frequency conversion, digitization, radio frequency (RF) oscillators and waveform generation. While these are often accomplished by electronic means, they are limited in the bandwidth that they can cover. RF photonics has many advantages over these electronic counterparts. The ability to cover larger bandwidths, immunity to electromagnetic interference, low weight and stability are just some examples of these advantages. All of the above functions can be accomplished by photonics. An example of an RF oscillator based on photonic is shown in Figure 1.

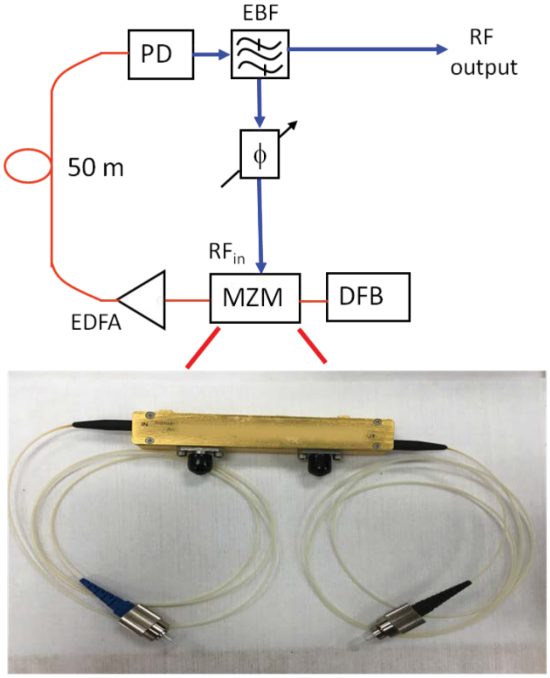

Figure 1: RF Photonic Oscillator using a Mach Zehnder Modulator

2. RF DOWNCONVERSION

A down converter is needed before signals can be digitized. For most wide band applications, an analog to digital converter (ADC) bandwidth of 500 MHz (with a sampling rate of 1 GHz) can operate with an effective number of bits (ENOB) of around 10. However the frequency of the signal to be digitized can be much higher than the ADC bandwidth. A downconverter can shift the frequency into the operational range of the ADC. An RF downconverter takes an RF signal, mixes it with a local oscillator (LO) and makes an intermediate frequency (IF). The IF output is the difference between the RF signal and the LO. The RF downconverter has the typical RF metrics of gain, noise figure and dynamic range.

2.1 RF Photonics Downconversion

A photonic based downconverter provides increased frequency range and dynamic range. A photonic downconverter appears in Figure 2. The RF signal is input to the first modulator, while the LO is input at the second modulator. The optical filter will then select out the pair of LO and RF sidebands. The LO and RF sidebands will be detected at the photodiode to an IF signal.

The photonic downconverter does have the advantage of wide bandwidth and image rejection. However it also has some limitations. When the optical carrier is filtered out, he total optical power at the photodiode is reduced. Therefore, the RF gain of the downconverter will be low. Also, the nonlinearity of the optical modulator will reduce the dynamic range of the IF. Other configurations can improve on these limitations.

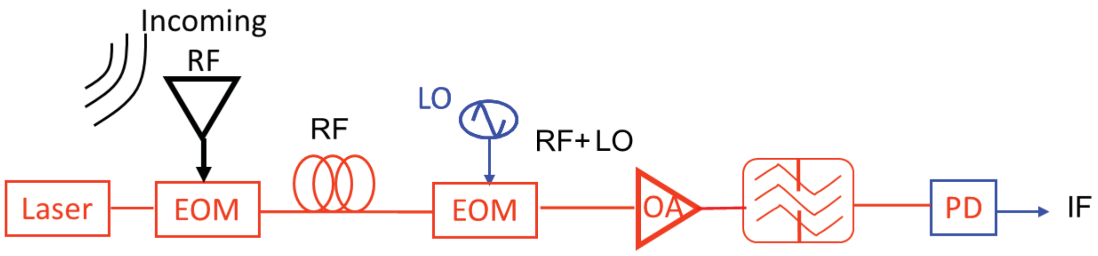

Figure 2: Block Diagram of a Serial Cascaded Modulator Photonic RF Downconverter
EOM: electro optic modulator, OA: optical amplifier, PD: photodiode

2.2 Advancements in RF Photonic Downconverters

Different architectures can improve on the previous architecture. In one example, a parallel modulator scheme can be employed for downconversion. The laser is split between two paths where the RF and LO are applied separately. After filtering, the RF and LO are combined and sent to a balanced photodiode. The system can improve the noise figure and gain when compared to the previous method. Unfortunately the parallel architecture is a large interferometer. The requirement to keep the two separate paths balanced adds complexity to the overall system.

Other methods can be used to downconvert the signal. Different modulators can be used in either of the above configurations. In either case, the needed performance will dictate which architecture will be used.

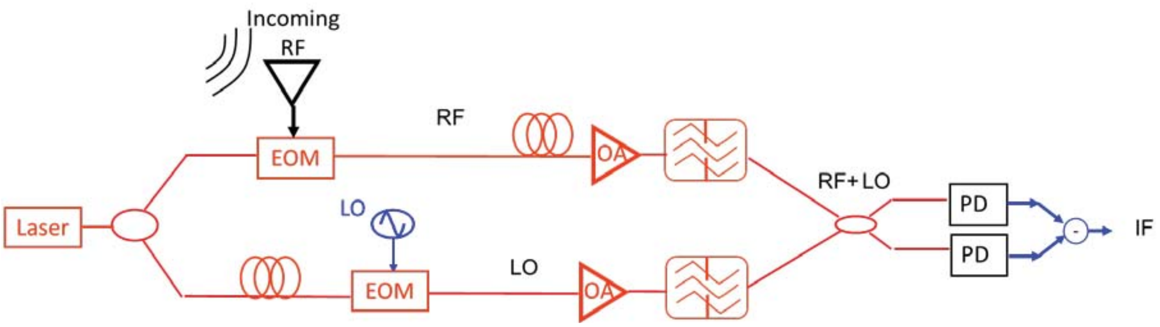

Figure 3: Block Diagram of a Serial Cascaded Modulator Photonic RF Downconverter

3. RF PHOTONIC OSCILLATORS

Since the downconverter requires a local oscillator, this is a good time to discuss RF photonics solutions for this application. The optoelectronic oscillator (OEO) is a good example. The OEO operates on the principle of using a long fiber delay line in order to create a cavity with a high Q. This in turn allows for the generation of very low phase noise RF clock signals. The OEO can be made in many different configurations. One example is shown in Figure 4. In this case the OEO is in a master slave configuration. The master OEO has a higher Q and imposes its phase noise upon the slave OEO. The lower Q slave OEO does not support the side modes of the master OEO. Therefore the result is a low phase noise RF signal without the spurious side modes.

While the OEO has the capability to generate very high quality RF clock signals, it is often fixed in frequency. For different applications, an oscillator that can be tuned very quickly over a large frequency range is of great importance. Another method for generating widely tunable RF signals is through the use of injection locking of lasers. Much like the OEO version above, a master laser is used to lock the phase of a slave laser. The two laser outputs are then beat at a photodiode, generating an RF tone. An example system is shown in Figure 5. By proper control of the amount of light that the master couples into the slave, and the wavelength difference between the two lasers, the frequency of the RF tone can be changed. The wavelength difference or the power can be changed electronically very quickly, and the corresponding change in frequency happens just as fast. An example of tuning the RF frequency over multiple gigahertz in a nanosecond is shown in Figure 5.

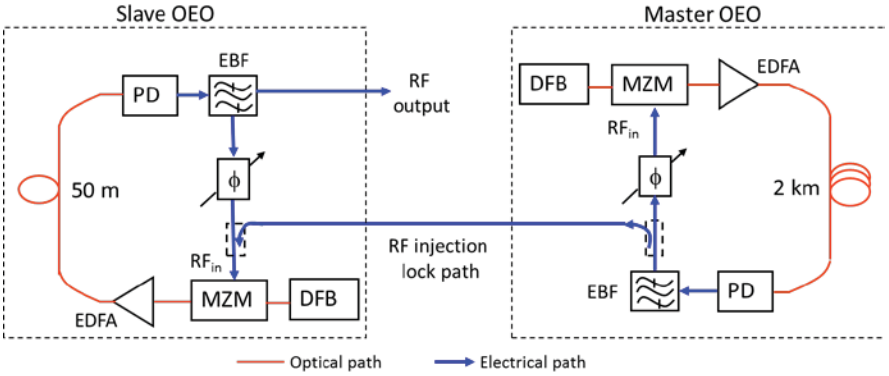

Figure 4: Master-Slave OEO Configuration

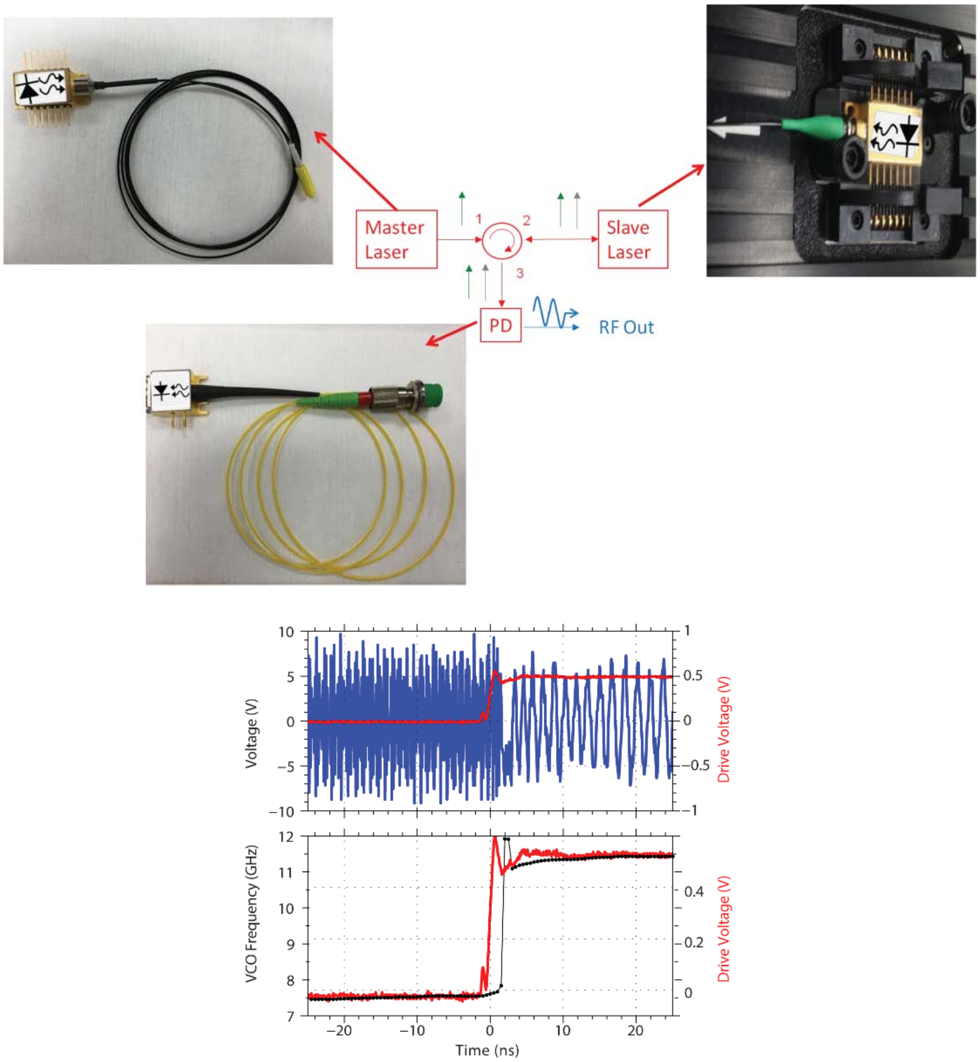

Figure 5: Laser Injection Locking Configuration and Tuning Results

4. RF PHOTONIC ANALOG TO DIGITAL CONVERSION

The need for a downconverter comes from the limited bandwidth of the electronic ADC. The bandwidth of the ADC is limited by noise sources in the electronic circuit. For high bandwidths, the clock jitter is the dominant noise source. ADC advancements have increased the bandwidths now possible. This is accomplished by parallelizing low bandwidth ADCs in order to increase the overall bandwidth. For N identical ADCs, the bandwidth increases by N times. The signal-to-noise ratio (SNR) performance is shown in Equation 1.

$$SNR_{total} = \frac{1}{\left((\varpi_{bw}\sigma_{tj})^2 + \frac{(\varpi_{bw}\sigma_{aj})^2}{N} + \frac{1}{N \times SNR_{th}} \right)} \tag{1}$$

where ω_{bw} is the bandwidth of the single ADC, SNR_{th} is the thermal SNR, σ_{tj} is the timing jitter and σ_{aj} is the aperture jitter. When the same clock is used for all of the ADCs, the timing jitter does not improve by parallelization. Figure 6 shows the SNR will decrease at higher frequencies, limited by the timing jitter.

Photonics may improve the performance when compared to just electronic solutions. Low phase noise is one of the assets of RF photonic sources as described in the previous section. Hybrid solutions using photonic sampler with electronic ADCs have been demonstrations. In addition, solutions using photonic quantization have been developed as well.

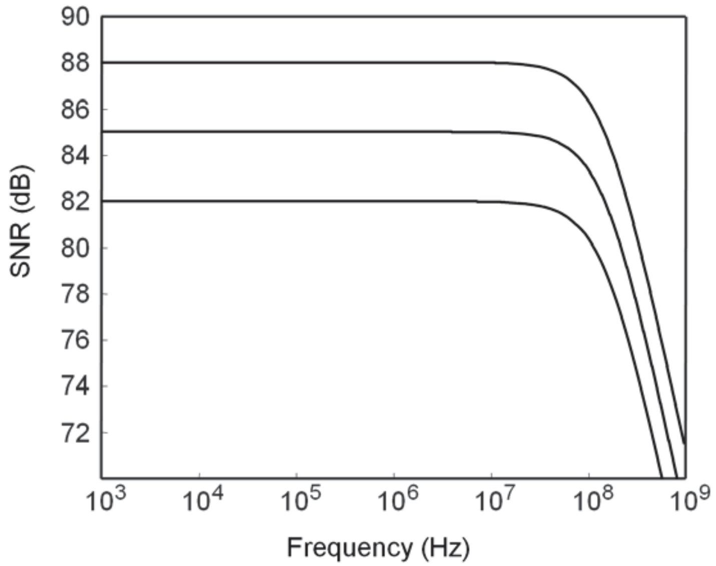

Figure 6: SNR versus Frequency for One, Two, and Four Parallel ADCs

4.1 RF Photonics Sampling with Electronic ADCs

Figure 7 shows a photonic sampling scheme. The amplitude of the pulses from a laser are modified by the RF signal to be sampled. The pulses are time demultiplexed and passed to multiple ADCs. The hybrid configuration combines parallel ADCs better clock jitter sampling.

Time demultiplexing is not the only way to do the operation. Instead multiple wavelength pulse sources can be used with a wavelength demultiplexer (WDM), in place of the switch. This configuration appear in Figure 8.

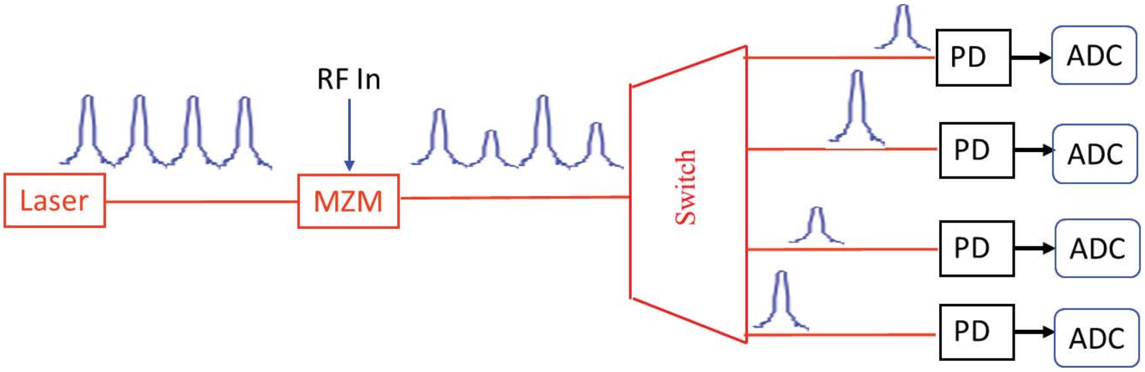

Figure 7: Photonic ADC using Optical Sampling and Time Switched Electronic ADCs

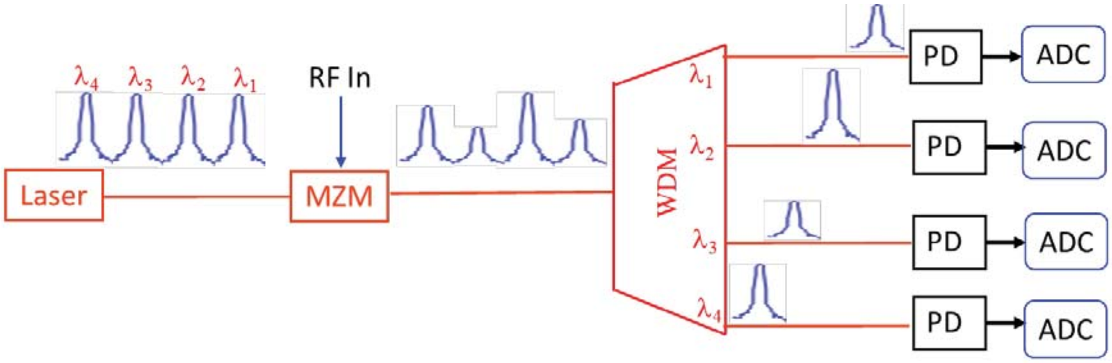

Figure 8: Photonic ADC using Optical Sampling and Wavelength Demulitplexed Electronic ADCs

A time stretch method is another hybrid method for improving ADC performance. Figure 9 shows the system. The laser produces multiple wavelength pulses that are not narrow but broad in frequency. After being modulated, dispersion will do a frequency to time conversion, stretching the signal in time. A WDM creates overlapping time blocks which then go to parallel ADCs. The advantage of time stretching is the overlapping time signals can be used to calibrate the delays between the various paths.

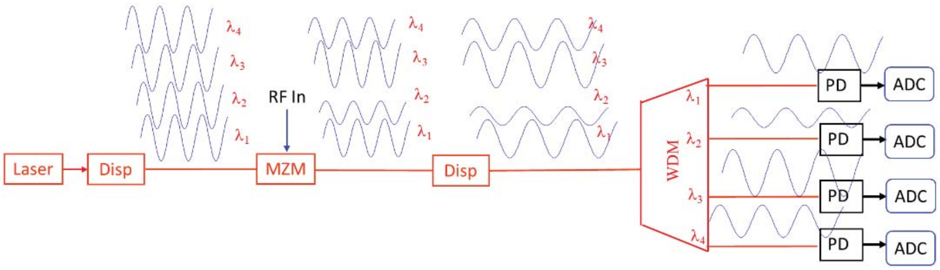

Figure 9: System using Time Stretching for Photonic ADCs

4.2 RF Photonics Sampling and Quantization

Photonic ADCs can also use photonic quantization One method is to use an array of modulators to perform the quantization function. Figure 10 shows two modulators, which are identical except for the Vpi. By setting the Vpi of one to half of the other, a two bit quantizer is achieved. Unfortunately this system has only been shown to have 4 bits of quantization.

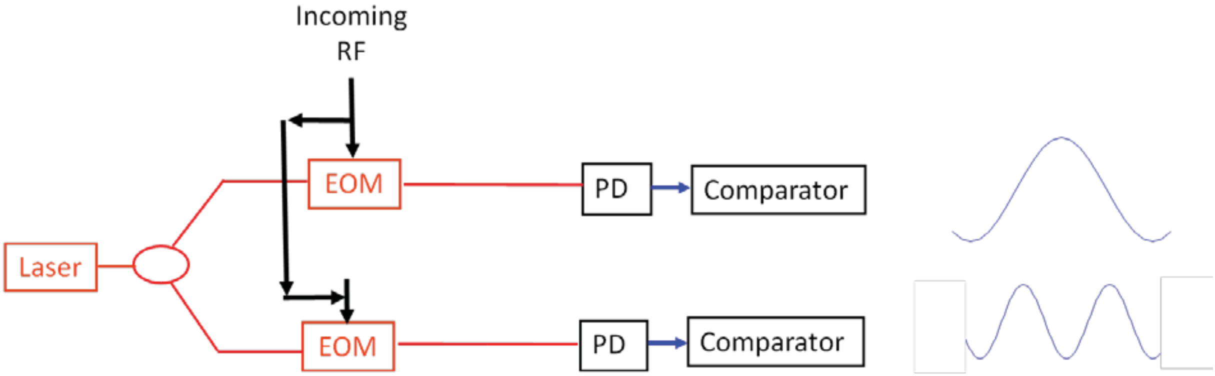

Figure 10: Photonic ADC with Optical Quantization of Two Bits

Another method for quantization is to use a nonlinear response. For example, a power thresholder can be used to quantize. Depending on the power of the signal the device will register it as either a one or a zero. A saturable absorber is one way to do thresholding. Figure 11 shows the response of a saturable absorber versus input power. When the power is below a certain level, the absorber has only a small amount of transmission. When the light gets stronger, the absorber will allow more light though. However the transition is not sharp enough to really accomplish the difference between a one and zero. To sharpen the transition, an optical cavity can be used. Different cavities can be used, including a Fabry Perot and a ring resonator. Examples of these types of filters appear in Figure 12 By placing the absorber in the cavity, it can shorten the amount of power between a transition between low and high transmission. The improved response is seen on the right in Figure 11.

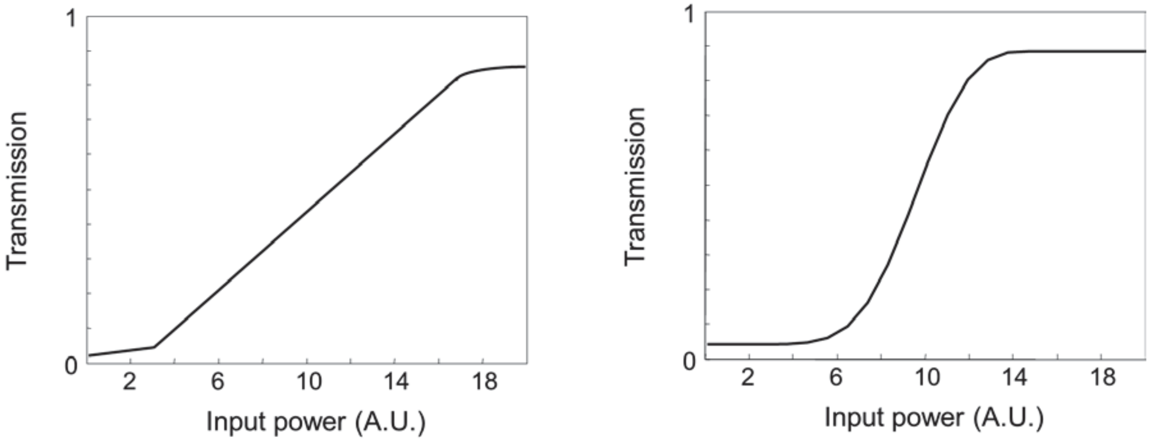

Figure 11: Transmission Versus Input Power for Saturable Absorber (left) and Saturable Absorber in a Cavity (right)

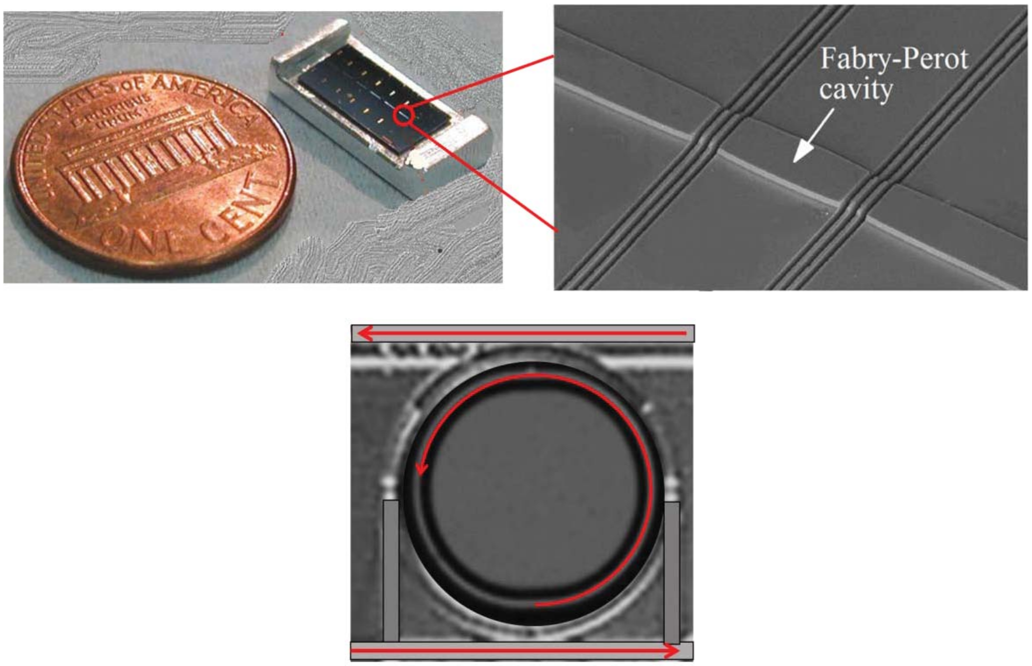

Figure 12: Fabry Perot and Ring Resonator Filters

5. RF PHOTONIC WAVEFORM GENERATION

Another signal processing application is waveform generation. Beyond just a single RF tone, which can be generated by the RF photonic oscillators described in a previous section, waveform generation involves creating complex waveforms. RF photonic can be used for generating waveforms.

Figure 13 shows an optical source that has a large optical bandwidth. A spatial light modulator (SLM) acts as a spectral filter. A dispersive element then acts as a wavelength to time transform. This is similar to the time stretch process in the photonic ADC discussion. After being detected at a photodiode, the resulting time varying signal is created. The SLM is often realized by using a liquid crystal array.

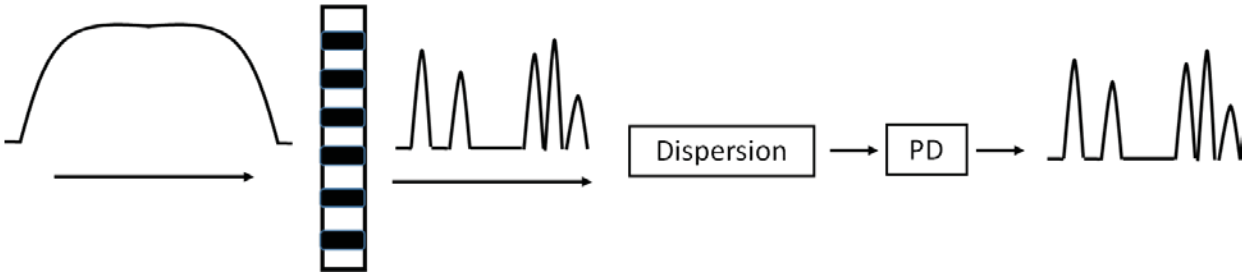

Figure 13: Waveform Generation using a Spatial Light Modulator and a Broadband Optical Source

Another method is to use an optical comb source. The wavelength spacing between the comb lines can be made to match the channel spacing of a fiber based arrayed waveguide grating (AWG), as seen in Figure 14. The output of the AWG is connected to the SLM. A reflective surface can be used behind the AWG to reflect the modulated light back down the AWG. The recombined light will then pass through a fiber and be converted to a time varying electrical signal. The advantage of this configuration is the reduced size, as well as being realized without having to use free space elements.

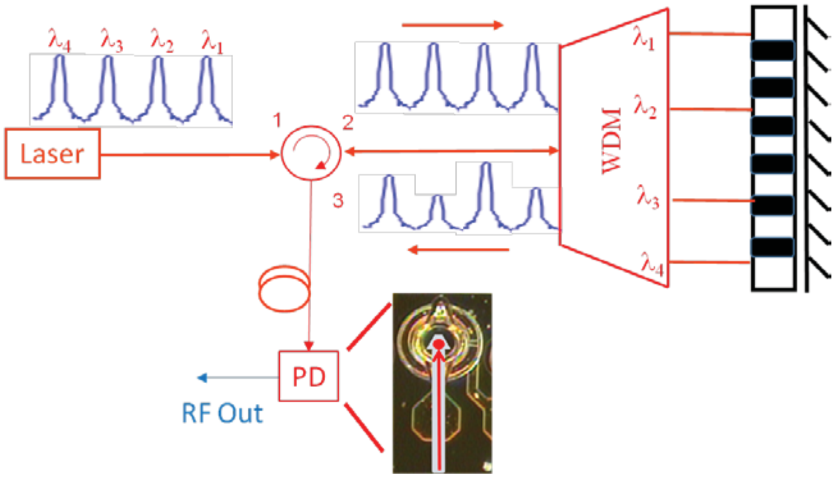

Figure 14: Waveform Generation using an AWG and a Spatial Light Modulator

6. CONCLUSIONS

Several different analog signal processing systems using photonics have been covered. These include a photonics-based RF downconverter, analog to digital converter, RF oscillator and an arbitrary waveform generator. A serial configuration, as well as a parallel structure, for downconverting signals has been covered. The RF oscillator for use with a downconverter has also been reviewed. The OEO can produce very low phase noise signals at a single frequency, while injection locked lasers can produce RF tones that can be quickly tuned over several gigahertz. Next the photonic-based analog to digital converter was presented as an alternative to just electronic ADCs. Hybrid photonic-electronic ADCs can overcome the timing jitter limitation of electronic clocks. In addition purely photonic based ADCs which use optical quantization can also be used for ADCs. However these methods need more improvements before they can compete with hybrid solutions. Finally photonic-based waveform generation was covered. A SLM can be used to modify the spectrum of a broad optical source. Then the spectrum is converted into a time domain waveform that is detected, creating a new waveform in the electrical domain. Clearly RF photonics can be used in many areas of analog signal processing.

LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

ACRONYM	DESCRIPTION
ADC	analog to digital converter
AWG	arrayed waveguide grating
ENOB	effective number of bits
EOM	electro-optic modulator
IF	intermediate frequency
LO	local oscillator
OA	optical amplifier
OEO	optoelectronic oscillator
PD	photodiode
RF	radio frequency
SLM	spatial light modulator
SNR	signal to noise ratio
WDM	wavelength demultiplexer/division multiplexer