An RF Photonic Auto-correlator Using Sideband Dispersion in a Fiber Optic Loop

by Michael R. Stead, Weimin Zhou, and Ming-Chiang Li

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An RF Photonic Auto-correlator Using Sideband Dispersion in a Fiber Optic Loop

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We have demonstrated a new radio frequency (RF)-photonic, true time-domain auto-correlation processor using a fiber-optic recirculation loop circuit. An RF microwave input signal is carried by laser light using amplitude modulation and is sent into an optical fiber loop circuit. The dispersion of the optical fiber causes the two modulation sidebands to travel with slightly different speeds, creating a progressively larger phase delay with each transit around the loop. This stepped delay is used to perform the auto-correlation of the RF signal. This has potential applications such as an RF channelizer and spectrum analyzer for pulsed RF signals.
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1. Introduction

The need for high-bandwidth, high-speed, and high-resolution radio frequency (RF) and microwave systems continues to expand, with applications in surveillance, communications, RADAR, and signal/signature detection. We had previously conceived (1) and presented (2) an RF-photonic channelizer, which used a dual-path optical pulse replicating loop using two optical carriers to perform a true time correlation to achieve over 1-GHz bandwidth and narrower than 12-MHz resolution for a pulsed RF input signal. Recently, we discovered that using the dispersion effect of the regular optical fiber, a single optical carrier may generate the dual path of the RF signal carried by two optical sidebands, and therefore produce an auto-correlation process.

In this work, we present a simplified RF-photonic, fiber-loop auto-correlation processor architecture. The RF signal carried by the optical pulse is correlated with the two modulation sidebands of that pulse, which are created by the RF signal itself. Using an optical fiber loop of several kilometers in length, a time delay between the two sidebands is generated due to the nature of the optical fiber’s dispersion. This relative delay is compounded with each passage through the optical loop. We tap 5% of each replicated pulse out of the loop with a coupler. With a photodetector, we extract the RF signal pairs from the optical signal and the sidebands. A set of time-delayed, beating signals is correlated with a crystal detector, which yields the auto-correlation product terms, which are recorded with an analog-to-digital (A/D) converter. The data are Fourier transformed, and frequency information is extracted. We have demonstrated a 10-GHz bandwidth, single-pulse, time-domain auto-correlation processor/spectrum analyzer using this concept.

2. Theory and Concept

2.1 Autocorrelation Receiver

A true time-domain auto-correlation receiver performs a correlation between a signal and the same signal under a time delay. The frequency information can be obtained from a Fourier transformation of the time-domain correlation function. For this to be done experimentally, it is necessary that the signal be split or copied, so that a variable delay can be introduced to one of the two resultant signals, and—since many comparisons are necessary—so that they can be compared without destroying them. Digital auto-correlators accomplish this by sampling the time-domain, digitizing the input signal, and then performing the correlation mathematically. However, this requires that the input signal remains the same during the whole correlation processing time. In addition, the signals are intrinsically limited by their digitization speed.
2.2 Our Implementation

We accomplish this process by using a single-mode laser as an optical carrier for the RF via amplitude modulation. The RF-modulated laser light is sent to a recirculating loop circuit via a 1x2 optical switch (figure 1). Each pass through the loop introduces a relative time delay to the sidebands of the original signal. Since only a fraction of the light is tapped out of the loop, the signal continues to exist and evolve as it travels around the loop, with an additive time delay for each circulation. The replicas that are tapped out consist of a central optical frequency, carrying the RF signal, and the modulation sidebands, carrying the same RF, with a relative delay of ±nΔt, where n is the pulse replica number.

![Simple schematic of operational theory of the device.](image)

2.3 Sideband Creation and Generation of Delay

When an RF-signal (frequency = fRF) is applied to an optical carrier (wavelength = λc), a pair of optical sidebands is created with

\[ \lambda_s = \lambda_c / (1 +/- (\lambda_c f_{RF})/c). \]  

(1)

For RF frequencies small in comparison to the optical frequency, this simplifies to

\[ \lambda_s = \lambda_c +/- \Delta \lambda, \quad \Delta \lambda = (\lambda_c)^2 f_{RF}/c. \]  

(2)

For simplicity, we consider only one sideband. The correlation effect is dependent on the amplitude of the two signals being mixed, so sideband-sideband interactions are a second order effect, much smaller than center-sideband interaction.
For the fiber used in the experiment, Corning smf-28, the dispersion relation is, accurate from 1.2 to 1.6 microns, approximately (3):

$$D(\lambda) = \left(\frac{S_0}{4}\right)(\lambda - \lambda_0)(\lambda_0/\lambda)^3(\text{ps}/(\text{nm km}))$$

(3)

$$S_0 = 0.092 \text{ ps}/(\text{nm}^2\text{km}), \quad \lambda_0 = 1302 \text{ nm}$$

In equation 3, $\lambda_0$ is the minimum dispersion wavelength and $\lambda$ is the optical wavelength of the laser. Integrating $D(\lambda)$ from the optical carrier wavelength to the sideband wavelength and multiplying by the fiber length in kilometers ($L$) yields the time delay between the two, in picoseconds:

$$\Delta t = LS_0 \left[\left(\lambda_c^2 - \lambda_s^2\right) + \frac{\lambda_0^4}{4}\left(\lambda_c^{-2} - \lambda_s^{-2}\right)\right]/8$$

(4)

Each passage through the loop adds an additional $\Delta t$ of relative delay for the sideband. This allows a correlation to be performed with a delay of $\Delta t$, $2\Delta t$, $3\Delta t$ … $n\Delta t$, where $n$ is the total number of pulse replicas generated.

### 2.4 Correlation

The central optical carrier and the delayed sidebands drive a high-speed optical detector. The electrical signal generated consists of the original RF combined with time-shifted copies of itself. If the original signal were $W(t)$, the output of the detector would be $AW(t)+B[W(t+\Delta t)+W(t-\Delta t)]$. This is fed into a mixing, nonlinear crystal detector, which generates the correlation coefficients. The amplitude of the output of the crystal detector is dependent on both the amplitudes of the input signals, and their phase separation. These coefficients are recorded by an analog-to-digital convertor (ADC) and digitally Fourier transformed, allowing the frequency information to be extracted.

### 3. Experiment

#### 3.1 Experimental Setup

The actual setup used to perform the experiment is shown in figure 2. An RF signal (up to 12 GHz) is sent to the modulator element of an electro-absorption modulated laser (EML) operating at 1556.56 nm. This produces an RF signal on an optical carrier. A pulse (18 $\mu$s) is created with a lithium niobate (LiNbO$_3$) modulator with a 33-dB contrast ratio. The pulse is switched into the loop with a fast 1x2 optical switch. In addition, a slow, high-contrast ratio switch (>60 dB) cuts off further input to the loop. This switch is used because the LiNbO$_3$ modulator and the fast optical switch do not have sufficient contrast to eliminate unwanted signal injection entirely, while the isolation switch lacks the speed to create a short pulse. The loop consists of approximately 7.5 km of smf 28 optical fiber. Within the loop, there is a 5% optical
tap, which samples each replicated pulse; an erbium-doped fiber amplifier (EDFA), which compensates for the loss in transit through the loop; an optical filter, which reduces the amplified spontaneous emission of the EDFA; and an isolator to eliminate reflected signals. The transit time for the loop is approximately 37 μs. The pulse sent through the loop is an 18-μs-square pulse. At no time does the relative delay approach the same order of magnitude as the pulse width, so there is always adequate overlap, and there is never overlap from one pulse to the succeeding replica.

Upon exiting the loop, the optically carried RF is amplified with an EDFA to more fully use the dynamic range of the high-speed optical detector. The output from the detector is amplified by a +10 dB RF amplifier. Any DC is filtered with a DC block, then the signal is sent to a crystal detector, in which mixing occurs. The output from the crystal detector, which represents the correlation coefficients, is sent to an ADC, sampled at 1 megasample per second. The information is recorded on the PC. The digitized data is processed, yielding amplitude as a function of pulse number. A Fourier transform is performed on this data.

### 3.2 Data

The mapping into the frequency domain of the results of the Fourier transform is more complicated than in the case of a standard auto-correlation. Normally, the results would be such that the frequency of each element “N” would be determined by $f_N = (N/M)f_{\text{max}}$, where $f_{\text{max}}$ is the
maximum bandwidth of the correlator, and M is the number of elements in the transform. Because the dispersion-created $\Delta t$ is dependent on $f_{RF}$, our transformed data has a nonlinear frequency distribution. It can be derived from the dispersion relation. The frequency corresponding to each element, N, of the transformed data is defined by

$$f(N) = \Delta t N / M,$$

where $M$ is the total number of points in the transform. However, unlike most correlation transforms, $\Delta t$ is dependent upon $f$ as defined by equation 4. Combining equations 4 and 5, and assuming that the sideband separation is small compared to the optical wavelength of the laser yields

$$f(N) = 2 \left[ \frac{cN}{(S_0LM)} \right]^{1/2} \left[ \frac{\lambda_c^3}{\lambda_0} - \frac{\lambda_0^4}{\lambda_c^4} \right]^{-1/2},$$

where $c$ is the speed of light, $L$, $S_0$, $\lambda_c$ and $\lambda_0$ are defined previously. Data were taken for several different single input frequencies of RF modulation. The data were transformed and plotted in figure 3.

![Figure 3. Transformed data. Input frequency is indicated in legend.](image)

While there is considerable noise and some spurious features, the input frequencies are clearly recovered.
4. Conclusion

The principle of performing an auto-correlation on a RF signal using only a dispersive optical fiber-loop circuit to yield frequency information about the RF frequency with a single input pulse has been demonstrated. The results of the correlation yield a nonlinear density of frequency channels, which could have new applications in pulsed signal processing techniques with low-cost and simple RF-photonic circuitry.
5. References


2. Stead, M.; Zhou, W.; Li, M.-C. Demonstration of an RF-Photonic Microwave Channelizer Using an Optical Fiber Recirculating Loop, 2008 Army Science Conference.

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<tr>
<th>Symbol</th>
<th>Definition</th>
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<tr>
<td>A/D</td>
<td>analog-to-digital</td>
</tr>
<tr>
<td>ADC</td>
<td>analog-to-digital convertor</td>
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<tr>
<td>EDFA</td>
<td>erbium-doped fiber amplifier</td>
</tr>
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<td>EML</td>
<td>electro-absorption modulated laser</td>
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<tr>
<td>LiNbO₃</td>
<td>lithium niobate</td>
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<td>RF</td>
<td>radio frequency</td>
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