# Using Dispersion in a Fiber-Optic Loop to Perform Time Domain Analogue RF Signal Auto-Correlation

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**Abstract:** We present an RF-photonic time-domain auto-correlator using a dispersion-induced stepped-time-delay of the modulation sidebands produced by a fiber optic recirculation loop circuit. This allows spectrum analysis of a single RF-pulse.

## 1. Introduction

We had previously conceived [1] and presented [2] an RF-photonic channelizer which used a dual-path optical pulse replicating loop with two optical carriers to perform a true time correlation. We achieved 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 standard 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 optical carrier, 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 each replicated pulse out of the loop with a coupler. With a photodetector, we extract the RF signal from the optical carrier and the step-time-delayed sidebands. They are correlated in a crystal detector, which yields the beating signals of the auto-correlation products. These are recorded with an 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

The system architecture of the RF-photonic time-domain auto-correlator is shown in Fig. 1. An RF signal, $E(\omega_{RF}t)$ carried on a laser beam is fed into a long fiber-optic loop via a fast switch to create a "square pulse". The RF creates modulation sidebands separated from the optical carrier by the frequency of the RF, $\omega_{RF}$ ($=2\pi f_{RF}$). The sidebands travel through fiber at different speeds due to dispersion, governed by the relation,

$$D(\lambda) = \frac{S_0}{4}\left(\lambda - \frac{\lambda_0^4}{\lambda^3}\right)\text{ps/(nm}^2\text{km)},\ \ \lambda_0 = 1302\text{ nm},\quad (1)$$

where $\lambda$ is the wavelength of light, and $\lambda_0$ is the zero dispersion wavelength and the constant, $S_0$ is 0.092 ps/(nm$^2$km). This is accurate for wavelengths between 1200 and 1600 nm [3]. With $f_{RF}$ (<12 GHz) small compared to the optical frequency (~200 THz), the sidebands are essentially equidistant from the carrier in wavelength as well as frequency. Integrating $D(\lambda)$ from one sideband wavelength to the other, and multiplying by the fiber loop length in km (L) yields the time delay between the two, in picoseconds, for a single transit through the loop:

$$\tau = \frac{LS_0}{8}\left[(\lambda_2^2 - \lambda_1^2) + \lambda_0^4(\lambda_2^{-2} - \lambda_1^{-2})\right],\quad (2)$$

where $\lambda_{1,2}$ are the sideband wavelengths. When the sideband separation is small compared to the difference between the laser wavelength, $\lambda_L$=1556 nm, and the zero-dispersion wavelength, $\lambda_0$=1302 nm, we can write that $\lambda_2 - \lambda_1 = 2\Delta\lambda = -2\lambda_L^2 f_{RF}/c$, where c is the speed of light. Then, equation (2) reduces to:

$$\tau = f_{RF}\,(LS_0/2c)(\lambda_0^4/\lambda_L - \lambda_L^3), \quad \text{or} \quad \tau = \omega_{RF}\tau_0, \quad (3)$$

where $\tau_0 = (LS_0/4\pi c)(\lambda_0^4/\lambda_L - \lambda_L^3)$ is a constant. Therefore, each passage through the loop will add an additional $\tau$ of relative delay for the sideband. This creates a train of pulses emanating from the tap with sidebands delayed by $\tau$, $2\tau$, $3\tau$ … $n\tau$, where n is the total number of pulse replicas generated. The RF signal carried by both sidebands is extracted from the optical carrier with a high-speed detector, and sent to a mixing crystal detector. For each replicated pulse, the output from the crystal detector is the correlation coefficient between a pair of RF signals generated by the two sidebands with corresponding delay: $E(\omega_{RF}\,t)\times E[\omega_{RF}\,(t-k\tau)]$, where k represents the $k^{th}$ replica. A low pass filter removes the high-frequency components. The average amplitude of each baseband correlation coefficient, $A\,exp(ik\omega_{RF}\tau)$ is determined, and these amplitudes are digitally Fourier transformed to yield frequency information, where A is an amplitude constant dependent on the input RF amplitude. Because $\tau$ is dependent on the input RF frequency, the transform does not return a simple linear frequency scale. However, in practice, if the bandwidth of interest is smaller than the center frequency of the band, and the wavelength spacing between the two sidebands is much smaller than the spacing between the zero-dispersion wavelength and the laser wavelength, the time delays will be $k\omega_{RF}\tau_0$, and the correlation coefficients will be $A\,exp(ik\omega_{RF}^2\tau_0)$. Therefore, one can perform a simple Fourier transformation between time space "k" and frequency squared space, $\omega_{RF}^2$, to obtain useful frequency information.

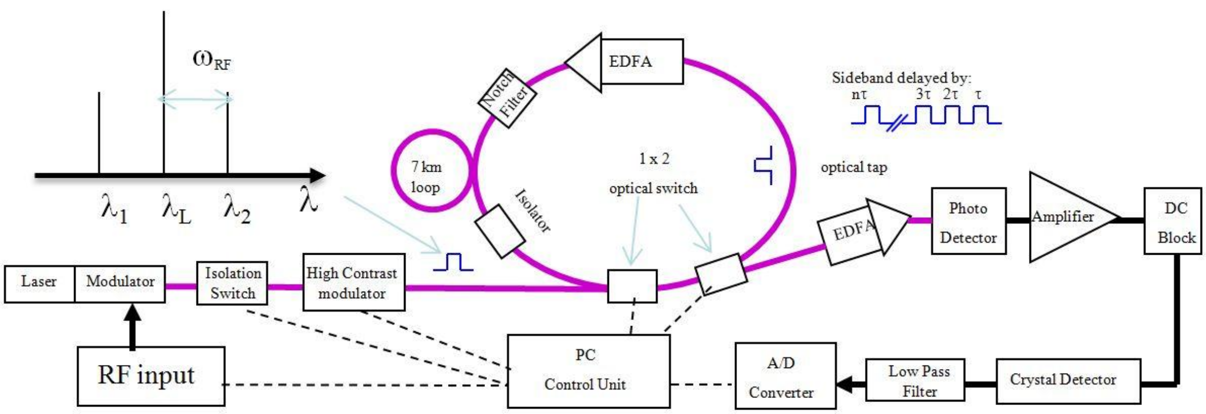


**Figure 1.** Detailed representation of experimental system. The purple lines are the path in the optical fiber. The heavy black lines are electronic signal lines. The dashed black lines are experimental control lines. The tapped output is a string of replicated pulses, each with its sideband delayed by a multiple of $\Delta t$

### 3. Experiment Results

An RF signal (up to 12 GHz) is sent to the modulator element of a single mode externally modulated laser (EML) operating at 1556.56 nm. This produces an RF signal on an optical carrier. A pulse (18 μs) is created with a $LiNbO_3$ 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 8 km of optical fiber. Within the loop, there is a 1x2 fiber optical tap, which samples the pulse in each transit; 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 (ASE) of the EDFA; and an isolator to eliminate reflected signals. The transit time for the loop is approximately 39.44 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. Figure 2 shows the raw experimental data obtained at the output of the RF crystal detector/low pass filter for two comparison experiments to prove the effects of the dispersion cause the correlation. We use the same RF signal input for both experiments with identical set-ups, except for the type of optical fiber. The first experiment uses standard Corning smf-28 fiber, and the data shows that the amplitude of the beating pulse pairs oscillates. We then repeated the experiment by replacing the fiber loop with a dispersion-shifted fiber ($\lambda_0$ nearly equal to $\lambda_L$). The oscillations disappear, though there are some minor fluctuations due to the properties of the EDFA, but these are not dependent on the RF signal. This comparison experiment proved that the beating is caused by the dispersion between the two sidebands.

We performed the correlation experiments using standard fiber for several different input frequencies from 6 to 12 GHz. The output from the crystal detector, which represents the correlation coefficients, is sent to an A/D converter, 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 these data and the results are shown in Fig. 3. 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 transform would be such that the resulting elements would be a linear progression of frequencies. Because the dispersion-created $\tau$ is dependent on $f_{RF}$, our transformed data has a nonlinear frequency distribution. Resolution becomes finer as frequency increases. For the 6-12 GHz frequency range, the experimental results show that, while there is considerable noise and some spurious features, the input frequencies are clearly recovered.

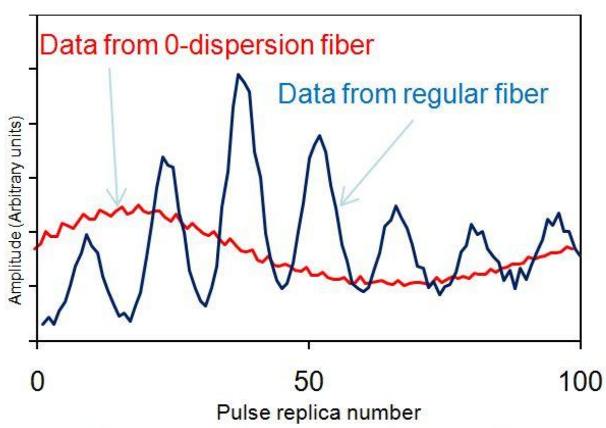


**Figure 2.** Raw data of the autocorrelated signal with the same RF input for the set-up with standard dispersive fiber (Blue); with zero-dispersion fiber (at 1550nm) fiber (Red). Each point is one pulse.

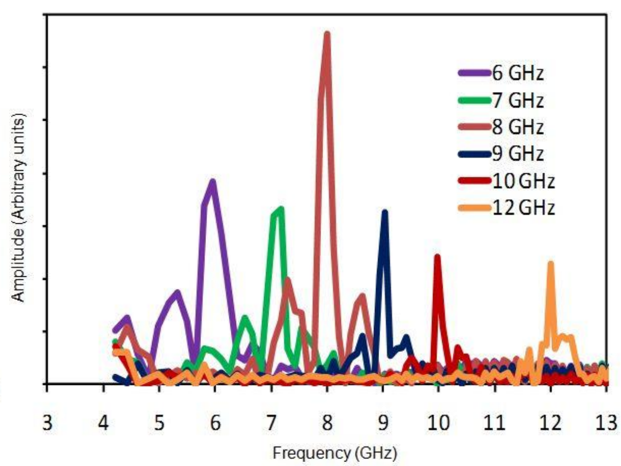


**Figure 3.** Results of Fourier transformation. Output frequency is indicated by the legend.

## 4. Conclusion

We have demonstrated autocorrelation of a single RF pulse over a broad frequency band. We have done this with a fiber-optic, pulse-replicating loop, using the inherent dispersion in the fiber to generate a stepped-time-delay between the sidebands of an optical carrier. This RF-photonic time-domain auto-correlator has potential new applications in pulsed signal processing, channelizing, and spectrum analyzing techniques. The simple RF-Photonic circuitry also has low cost, light weight advantages.

## References

[1] M.C. Li, "New Channelized Receiver" *Transaction of the AOC, 1,* pp 76-97 (2004); M. Li and W. Zhou, "Method of constructing a RF microwave true time domain auto-correlation receiver as channelized receiver using photonics" *Invention disclosure, ARL-08-40,* 2008

[2] M. Stead, W. Zhou, M.C. Li, "Demonstration of an RF-Photonic Microwave Channelizer Using an Optical Fiber Recirculating Loop", *Proceedings of the 26th Army Science Conference*, 2008.

[3] Corning document PI1036, April 2002.