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# Bi-directional frequency shifting loops for real-time processing of broadband RF signals

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**Abstract.** Analog photonic techniques can perform better than conventional digital electronics, which have significant limitations when it comes to processing fast RF signals on the fly. We show that a simple photonic architecture, based on a bi-directional frequency-shifting loop, makes it possible to calculate in real time the cross-correlation function of two broadband signals for about 200 values of their delay simultaneously. Additionally, our architecture also enables to perform spectral analysis of signals with 16 GHz instantaneous bandwidth, 100 % probability of interception, and detection electronics below 10 MSa/s.

## 1 Introduction

Digital electronics is the reference technique for signal processing. However, the race for processing speed has two limits. The first one is related to the clock noise of analog-to-digital converters, which limits the fidelity of the sampled signal. The other one is related to the capacity to process large data streams in real time. These limits become critical for real-time processing of multi GHz bandwidth signals. Today, the best real-time spectrum analyzers are limited to 1 GHz instantaneous analysis bandwidth, an obstacle for several applications, including correlation or spectral analysis of fast and broadband signals. On the contrary, analog approaches are free of these limitations. Their application in photonics is particularly interesting, owing to the high bandwidth, small size and low power consumption of optical components. Different approaches have been demonstrated so far, but they generally fail to simultaneously offer simplicity, frequency resolution, and low acquisition speed of the output signal [1]. Here, we describe a simple architecture that allows real-time analog processing of broadband signals (> 10 GHz bandwidth). Our architecture, which overpasses the performance of digital electronics, is based on a simple bi-directional frequency shifting loop.

## 2 Principles

A frequency shifting loop includes a frequency shifter, an amplifier whose function is to compensate for losses, and a filter which controls the spectral width of the signal and reduces the ASE emitted through the gain medium of the amplifier [2]. When this loop is injected by a continuous laser, it produces an optical frequency comb containing typically $N$ =200 lines spaced by the shift frequency. In microwave photonics applications, the loop is usually injected by a CW laser modulated by the RF signal of interest. It produces replicas of the input signal, shifted both in time (by the loop travel time), and in frequency (by the shift frequency per turn). It can be shown that when the product of the travel time and the shift frequency is an integer, the intensity of the output signal reproduces in time the spectrum of the input signal ("frequency to time mapping"), which validates the use of these systems for spectral analysis [3]. However in this case, the analysis bandwidth is small (a few 10s of MHz), and the acquisition rate must exceed the GS/s. These drawbacks can be overcome by using a double, or bi-directional frequency shifting loop.

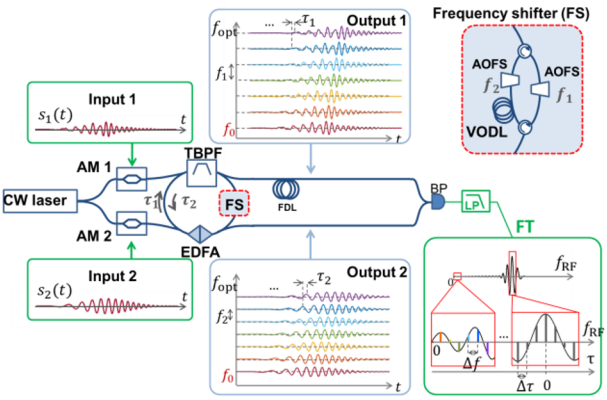


Fig.1 Architecture of the bi-directional frequency shifting loop (see text). AM: amplitude modulator, TBPF: tunable bandpass filter, EDFA: erbium-doped amplifier, FDL: fiber delay line, VODL: variable optical delay line, BP: balanced detector, LP: low-pass filter, AOFS: acousto-optic frequency shifter. The Fourier transform (FT) of the output signal maps in frequency the cross-correlation function of the signals $s_1(t)$ and $s_2(t)$.

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Introducing $s_{1,2}(t)$ the input signals under test, the electric fields at the outputs of the loop write: $E_{1,2}(t) = E_0 e^{i2\pi f_0 t} \sum_{n=0}^{N} s_{1,2}(t - n\tau_{1,2})\, e^{i2\pi n f_{1,2} t} e^{-i\pi f_{1,2}\tau_{1,2} n^2}$, where $f_{1,2}$ and $\tau_{1,2}$ are respectively the frequency shifts per roundtrip and the roundtrip times in the two ways of the loop. We assume that the system is set, so that $f_1\tau_1 = f_2\tau_2$. Then, it can be shown that the recombination of both fields on a detector provides the output signal: $V(t) = \sum_{n=0}^{N} < s_1(t)s_2(t - n\Delta\tau) > e^{-i2\pi n\Delta f t}$ where $\Delta\tau = \tau_2 - \tau_1$ and $\Delta f = f_2 - f_1$. Therefore the Fourier transform of $V(t)$ provides the cross-correlation function of $s_1$ and $s_2$, for about 200 values of their relative delay simultaneously. The time step of the correlation is $\Delta\tau$, and can be arbitrarily small. In practice, the sampling rate of $V(t)$is a few MSa/s. In the other case where the input signals are identical, the output signal writes: $V(t) = \sum_n < s(t)s(t - n\Delta\tau) > e^{-i2\pi n\Delta f t}$, which appears as the Fourier transform of the auto-correlation function of $s(t)$ , i.e. as the power spectrum of $s(t)$. Then, the architecture provides the power spectrum of the input signal mapped in the temporal domain.

## 2 Experimental results

### 1.2 Correlation of RF signals

In a first step, the architecture is used as a correlator. The two input signals are applied to two amplitude modulators, before entering the double loop (see Fig. 1). The output signal is acquired by means of a balanced detector, filtered, and digitized. As said, the Fourier transform of the output signal provides the cross-correlation function. We use this property to carry out a time difference of arrival experiment (TDOA), allowing us to locate a broadband transmitter (Fig. 2) [4].

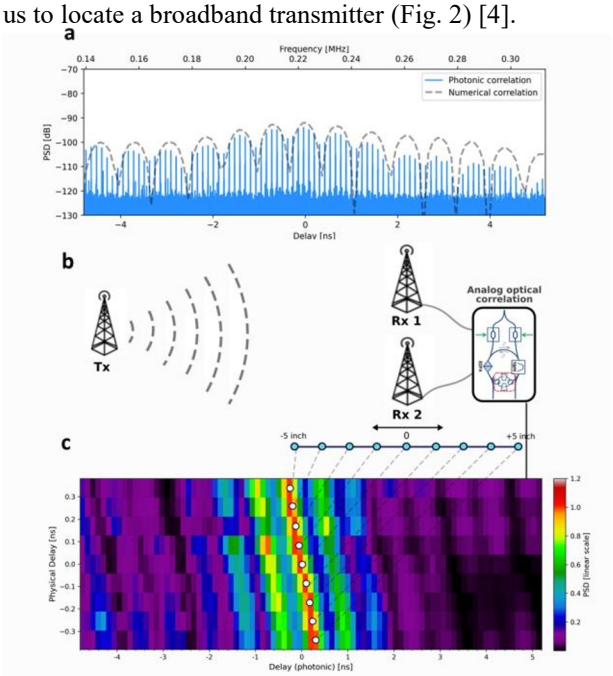


Fig.2 a: Cross-correlation trace (in blue) obtained for a broadband input RF signal emitted by a remote antenna (Tx) (central frequency: 0.7 GHz, bandwidth: 0.5 GHz) and comparison with the numerical correlation function (dash line). b: Sketch of the experimental TDOA set-up. c: Cross-correlation function as a function of the position of the receiver Rx2. The correlation function shifts with the physical delay between the receivers.

### 1.3 Real-time spectral analysis

In a second time, we illustrate the interest of the architecture for the spectral analysis of broadband signals. In this case, the laser is modulated by the signal under test before being separated and sent into the loop. In Fig. 3, the input signal is the ambient laboratory RF noise, picked up by a broadband antenna, and amplified. The system enables to monitor in real time different frequency bands (e.g. telephony, wi-fi) simultaneously, with a frequency resolution of 150 MHz, a temporal resolution of 50 µs, a 100 % probability of intercept, and within a maximum bandwidth of 16 GHz (here, 8 GHz).

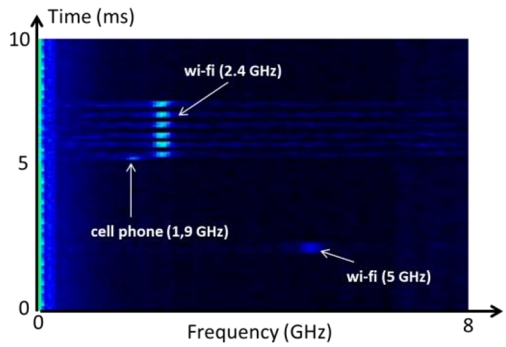


Fig.3 Experimental spectrogram of the ambient RF noise in the lab. The spectral bandwidth is 8 GHz, the time acquisition window is 10 ms long.

## 3 Conclusion

We have developed an original and compact architecture based on a bi-directional frequency-shifting loop, allowing real-time processing (cross-correlation, spectral analysis) of RF signals in the 0-16 GHz range. The striking simplicity of the system suggests possibilities for integration, leading to future embedded applications.

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