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Optical Phase Shifting Fourier Transform Scanning for Bandwidth-Efficient Blind RF Spectrum Sensing

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Abstract *Avoiding high-speed electronics, optical time-stretch Fourier transform scanning for RF spectrum sensing is presented. Broadband RF frequency scanning is achieved by using a phase shifting Mach–Zehnder interferometer. GHz RF signals have been detected with only 50 MS/s sampling rate.*

Introduction

Detection of high-frequency RF signals with unknown frequency components, which is crucially important for various applications in wireless communications, radar, cosmology and electronic warfare, requires high sampling rate at the receiver end due to well-known Shannon-Nyquist theorem. Requirement of large detection bandwidth can be greatly reduced by using photonic time stretch (PTS) analog-to-digital conversion concept [1], which uses chromatic dispersion to further stretch a chirped optical pulse carrying input RF signals leading to a slowed version of the original high-frequency RF signal. Despite the reduced detection bandwidth, it takes longer time to capture a given RF signal. Therefore, time-bandwidth product of the detection system, or total captured data volume, is always unchanged.

Recently, photonic time stretch compressive sensing (CS) [2-4] has been proven as a promising solution for data-compressed high-frequency RF signal detection. However, existing photonic CS approaches fall short in two aspects: (1) Nyquist rate pseudo-random bit sequences (PRBS) are required for time domain random mixing, which still suffers from electronic bottleneck. (2) By its nature, CS approach only works for spectrum-sparse RF signals and would fail for broadband RF signals. To address the first issue, we have recently demonstrated an all-optical time stretch compressive sensing method for RF signal detection based on spectral random mixing [5]. Alternative methods are highly demanded to tackle the second challenge.

Four-step phase shifting Fourier spectrum scanning is a powerful tool for broadband signal and imaging acquisition [6] and its successful implementation in a PTS imaging system has been demonstrated [7]. However, expensive and sophisticated high-speed (GHz) arbitrary waveform generator is required to provide phase-shifted RF frequency scanning across the whole frequency band of interest. In this work, we propose and experimentally demonstrate an all-optical PTS phase-shifting Fourier spectrum scanning approach for broadband RF signal detection based on spectral shaping using a phase-shifting Mach–Zehnder interferometer (MZI). Without using any high-speed electronic signal generator, modulator and photodetector, this method achieves data compression and completely eliminates the electronic bottleneck in high-speed RF spectrum sensing.

Principles

The proposed optical Fourier spectrum scanning is implemented in the optical spectral domain using an optical fiber MZI configuration, which include variable optical delay line in one arm and phase modulator in another arm. Due to wavelength-to-time mapping in PTS process, this spectral filter equivalently produces phase-shifting RF frequency carriers. Broadband frequency sweeping is realized by tuning the time delay in MZI and RF phase shifting is introduced by modulating the optical phase in one arm of the MZI. The key advantage of this method is that extremely high frequency and broadband RF frequency sweeping can be easily implemented in optical domain by tuning the free spectral range (FSR) of the MZI without using high-frequency signal generator and modulator. Note that both time delay tuning and optical phase modulation are implemented at a low speed as same as the pulse repetition rate (50 MHz in this work), which does not require high-speed electronics. With this approach, we demonstrate successful Fourier spectrum reconstruction of a single tone 1GHz, and dual tone (1GHz, 2.5GHz) RF signals using only 50 MS/s sampling rate.

Schematic of the proposed experimental setup is shown in Fig.1. A passively mode-locked fiber laser (MLL, Calmar Mendocino FP laser) generates a series of ultrashort optical pulses.

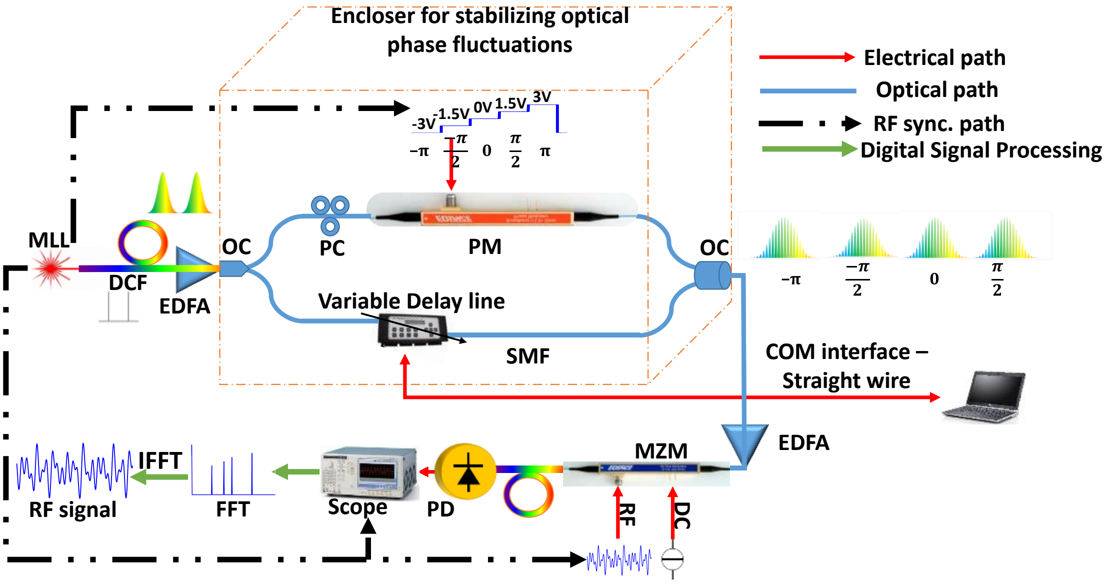

Fig. 1 : Schematic of Proposed system. MLL: Mode-Locked Laser, DCF: Dispersion Compensating Fibre, OC: Optical Coupler, PC: Polarization Controller, PM: Phase Modulator, MZM: Mach-Zehnder modulator, EDFA: Erbium doped fibre amplifier; RF: Radio Frequency signal, SMF: Single Mode Fibre, PD: Photodetector, FFT: fast Fourier transform, IFFT: Inverse fast Fourier transform.

Each pulse is time stretched using a dispersion compensating fibre (DCF) with total dispersion of 1 ns/nm to achieve frequency to time mapping. The time stretched pulse is amplified and directed to the Mach-Zehnder interferometric setup with one arm involving a programmable optical delay line. By tuning the optical delay Δt in the MZI structure, the change of carrier frequency in the encoded Gaussian pulse is given by

$$\Delta f_{RF} = \frac{c \times \Delta t}{\lambda^2 \times \ddot{\varphi}} \qquad (1)$$

where λ is the optical central wavelength of the laser and $\ddot{\varphi}$ is the group velocity dispersion of the DCF. In the other arm of the MZI, an electro-optic phase modulator is placed to introduce four discrete optical phase shifts using a staircase function with four different voltage levels synchronized with the MLL. Optical phase shifts will be converted to equivalent RF phase shifts after heterodyne detection at the PD. Hence, RF frequency generation is achieved by optical delay line and phase shifting is achieved by phase modulation. The output of MZI is a 4-phase shifted and RF frequency encoded Gaussian pulse, which serves as optical carrier to take the input unknown RF signal in a Mach-Zehnder modulator (MZM) biased at quadrature point. With fixed Phase modulation, the optical delay line is tuned to generate a series of phase shifted and frequency scanning RF modulated pulses. Integrating individual modulated optical pulses using opposite dispersion from a single mode fibre (SMF) generates four measurement components for each RF frequency scan under four-step phase shifting. Finally, full Fourier domain representation of the input RF signal can be reconstructed in digital domain.

Experiment Results

A proof of concept experiment has been designed and implemented based on conceptual schematic shown in Fig. 1. The optical time delay between paths of MZI converts to an RF frequency that can be described by eq. (1).

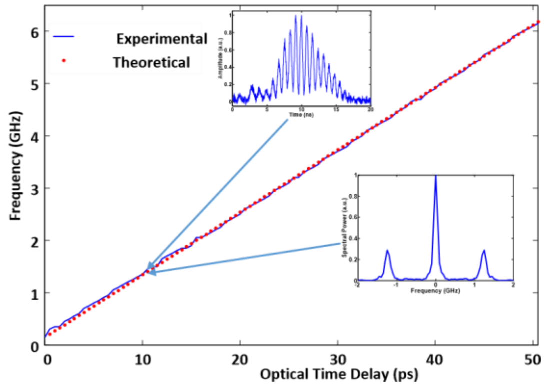

Fig. 2: Generated RF carrier frequency as a linear function of tunable time delay in the MZI.

Figure 2 shows the measured RF carrier frequency as a function of tunable time delay in the MZI. The delay changes from 0 to 50 ps in steps of 0.5 ps. A linear relation is clearly verified, which matches well with the theoretical results show in red. The insets show the time domain and frequency domain representations of encoded optical pulse at a particular optical delay of 10ps.

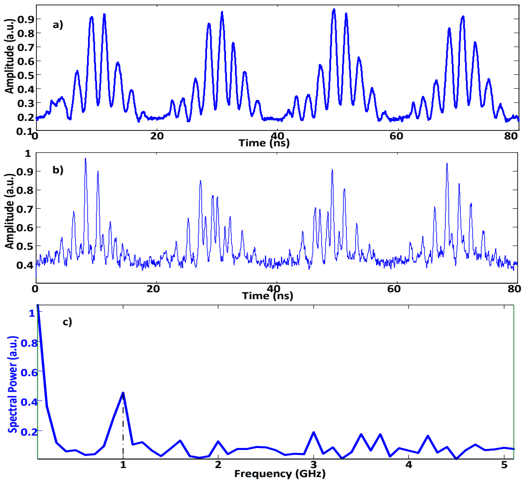

Fig. 3: Demonstration of single tone RF signal detection. (a) Phase shifted optical Gaussian pulses. (b) Modulated optical pulses by a single tone RF signal. (c) The reconstructed Fourier spectrum showing a strong single peak at 1 GHz.

A staircase signal with 1.5 V step size from -3 to 3 V is used to drive the phase modulator for every 100 ns, which covers five consecutive pulse periods with four periods for phase shifting and one pulse for phase reference. Figure 3(a) shows the generated four RF encoded optical pulses with 4-step phase shifting. Four optical pulses with the same scanning frequency are modulated by a single-tone input RF signal of 1 GHz with results shown in Fig. 3(b). This optical output is acquired and digitally summed to represent one single power measurement at a sampling rate of 50 MS/s. Frequency scanning is implemented by tuning optical delay at 50 MHz with a delay step of 1 ps, leading to overall 51 power measurements. The reconstructed Fourier spectrum is presented in Fig. 3(c) showing a strong single peak at 1.026 GHz.

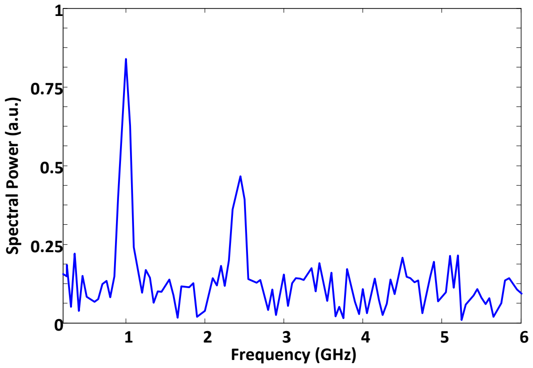

Fig. 4: Demonstration of dual tone RF signal reconstruction. Two peaks are clearly shown in the reconstructed Fourier spectrum.

Another demonstration with dual tone input RF signal at 1GHz and 2.4GHz with different amplitudes is presented. An improved time delay resolution of 0.5 ps is considered and totally 102 phase shifted measurements are recorded. The reconstruction result is shown in Fig. 4. As observed, two frequency peaks are found at 0.98 GHz and 2.43 GHz, respectively.

Conclusions

We propose and experimentally demonstrate a novel all-optical Fourier spectrum scanning approach for bandwidth efficient RF spectrum sensing. The method adapts photonic time stretch with optical spectral filtering to generate phase shifted RF frequency sweeping without using high-speed electronics for signal generation, modulation and detection. Therefore, electronic bottleneck in high-frequency RF signal detection is completely eliminated. As a proof-of-concept experiment, single-tone and dual-tone GHz RF spectrum detection has been demonstrated using only 50 MS/s sampling rate..

Acknowledgements

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