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Sparse Optical Arbitrary Waveform Measurement by Compressive Sensing

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***Abstract*—We propose and experimentally demonstrate a compressive sensing scheme based on optical coherent receiver that recovers sparse optical arbitrary signals with an analog bandwidth up to *25GHz*. The proposed scheme uses *16*× lower sampling rate than the Nyquist theorem and spectral resolution of *24.4MHz*.**

Keywords—compressive sensing, coherent receiver, microwave photonic, signal processing.

I. INTRODUCTION

Compressive sensing (CS) is a promising technique to recover bandwidth-limited signals with lower sampling rates than the Nyquist theorem [1]. By exploiting the prior knowledge of sparsity in imaging [2], photonic radar [3], and wireless over fiber [4] applications, CS can significantly reduce the required sampling rate for analog-to-digital converters (ADC). Several works in literature investigated the benefits of CS [5]–[7] in the optical domain. Although they studied different CS algorithms, the sparse signals for recovery are always considered as RF signals in the baseband. In this work, we proposed an optical coherent receiver based 'random demodulator [1]' compressive sampling scheme which can recover bandpass RF signals within *25GHz* analog bandwidth centered at the local oscillator (LO) wavelength. We experimentally demonstrated a spectral resolution of *~24.4MHz* across *25GHz* and a *16*× compressed sampling with respect to Nyquist rate.

II. RANDOM DEMODULATOR AND OPTICAL IMPLEMENTATION

The random demodulator receiver[1] consists of three main units: a pseudorandom number generator, a mixer, and an integrator (see Fig. 1 (b)). A received sparse signal $f(t)$ is mixed with pseudorandom numbers $p(t)$ generated at Nyquist rate, T_s. The mixed-signal is accumulated and sampled by a lower data rate ADC at MT_s. The received samples $s(kMT_s) = \sum_{i=kM}^{(k+1)M} f(iT_s)p(iT_s)$ are used to recover the discrete representation of the frequency spectrum of $f(t)$ as $F[k] = \sum_{i=0}^{N-1} f[i]e^{-j\frac{2\pi ik}{N}}$. N is length of the generated pseudorandom numbers, which are $p[k] \in \{-1,1\}$. An equivalent optical implementation of the random demodulator consists of using a coherent receiver as 'mixer', a binary phase-shift keying modulated (LO) as 'pseudorandom number generator', and low-pass antialiasing filter as an 'integrator'. The modulated LO signal called as 'sensing LO', $p_{LO}(t) = p(t)\cos(\omega_c^{LO}t)$, ω_c^{LO} is the LO angular frequency. The sparse signal $f(t)$ must be contained in the frequency band of $[\omega_c^{LO} - \frac{\pi}{T_s}, \omega_c^{LO} + \frac{\pi}{T_s})$. The CS based receiver operations can be written in a matrix form as follows: diagonal matrix $\boldsymbol{D}_{N\times N}$ with entries $D_{ii} = p[i]$, discrete Fourier transform in matrix form $\boldsymbol{F}_{N\times N}$ with entries $F_{ik} = e^{-j\frac{2\pi ik}{N}}$, and lowpass filter matrix $\boldsymbol{H}_{(N/M)\times N}$ with entries $H_{ik} = h[k - iM]$, where $h[k]$ is the impulse response of the lowpass filter. Then, in classical CS terminology, the measurement matrix is $\boldsymbol{V}_{(N/M)\times N} = \boldsymbol{HDF}$. The received N/M number of measurements form the vector $\boldsymbol{s}_{(N/M)\times 1}$, and the sparse discrete spectrum of $f(t)$ is $\boldsymbol{v}_{1\times N}$. Then least absolute shrinkage and selection operator (LASSO) can solve for ℓ_1 minimization:

$$\hat{v} = \arg\min_{v} \frac{1}{2}||\boldsymbol{s} - \boldsymbol{Vv}||^2 \ \ subject\ to\ ||\boldsymbol{v}||_1 < \tau$$

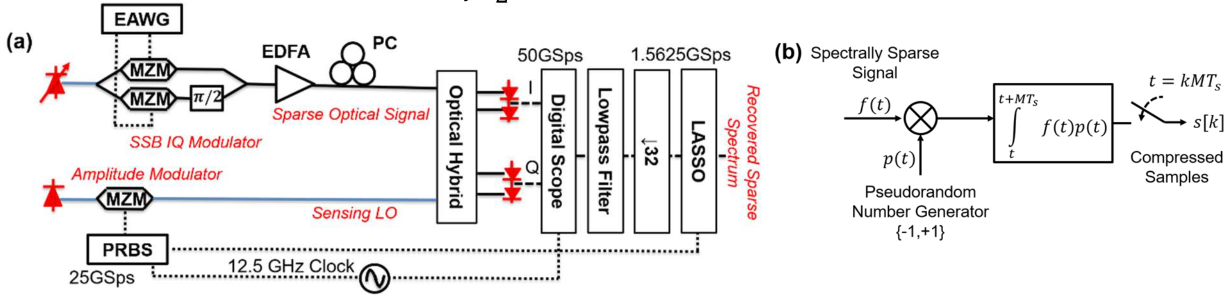

Fig. 1. (a) Experimental setup: --PM fiber, --SM fiber, erbium doped fiber amplifier (EDFA), Polarization controller (PC), electrical arbitrary waveform generator (EAWG), Mach-Zehnder Modulator (MZM), Pseudorandom bit sequence (PRBS), least absolute shrinkage and selection operator (LASSO), (b) The random demodulator receiver

The experimental diagram for the coherent random demodulator receiver is presented in Fig. 1 (a). Two distinct laser sources are used for LO and sparse optical signal generation. The LO laser operates at 1551.74 nm. A single side-band IQ modulator and a 25GSps electrical arbitrary waveform generator are used to generate arbitrary sparse bandpass signals. A Mach-Zehnder modulator with bias point at V_π generates a repetitive BPSK pseudorandom sequence with length of $N = 2^{10}$.The Nyquist rate for $p[k]$ is 25GSps. In a hardware implementation, the low-pass filter impulse response can affect the restricted isometric properties of the measurement matrix V. To observe this effect and fine-tune the low-pass filter characteristic for best results, we used a 50GSps digital scope, a digital low-pass filter. and a down-sample by 32 to emulate an analog lowpass filter and low-rate ADC. A digital 5th-order Butterworth filter with 0.5GHz 3dB bandwidth is used. Then, measured samples are feed to the LASSO optimizer. The scope and the PRBS generator use same clock source, and the PRBS is sent to the scope's third channel to construct the measurement matrix $\boldsymbol{V}$ for recovery.

III. RESULTS AND DISCUSSION

Two types of spectrally sparse signals are generated to test the performance of the proposed receiver: the chirped signals as $f(t) = e^{j\sum(\omega_i t + g_i(t))}$, where $g_i(t)$ can be a linear, quadratic, or sinusoidal function, as shown in Fig. 2 (a)-(d); and the constant spectrum over time signal as $f(t) = e^{j\sum(\omega_i t)}$ (see Fig. 2 (e)-(h)). We realized that with a compression rate of $M = 16$, seven distinct frequencies can be recovered with a 36 dB spur-suppression. The spectral resolution of this system is $25/N\ GHz \cong 24.41MHz$. Fig. 2 (h) shows that 50 MHz spaced peaks can be recovered successfully; however, the second carrier at -4GHz has a significantly smaller amplitude. The paper [1] presented the relationship between the sampling rate and the sparsity is $R \approx 1.7K\log(W/K + 1)$, where W is the Nyquist rate, K is the occupied spectrum, and R is the required sampling rate for perfect recovery. Future research for the CS receiver might be demonstrating this theoretical relation experimentally by tuning the sampling rate, the real-time and wideband implementation by using optical arbitrary waveform measurement techniques [8].

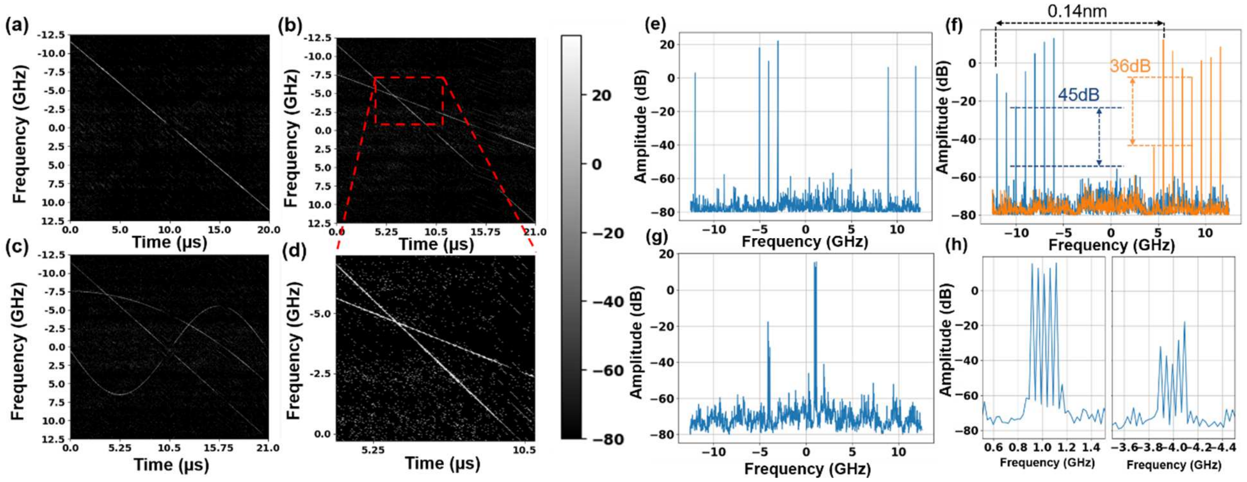

*Fig. 2. **Spectrograms:** (a) single linear chirped signal -12GHz to 12GHz, (b)two linear chirped signal -12GHz to 12GHz and -7.5GHz to 2.5GHz, (c)two nonlinear chirped signals; sinusoidal, quadratic, and single -12GHz to 12GHz linear chirped signal. **Constants spectrums:** (e) 6 RF tones, [-12,-5,-4,-3,9,12]GHz, (f) 7 RF tones at [-12,-11,-10,-9,-8,-7,-6], tunable laser tuned from 1551.74nm to 1551.88nm, (g)5 RF tones, [-100,-50,0,50,100]MHz at carrier frequencies 1GHz and -4GHz, (h) zoom in around the carriers at (g)*

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