Optics Communications 402 (2017) 119–122

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Single-pixel imaging based on compressive sensing with spectral-domain optical mixing

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A R T I C L E I N F O

Keywords:
Compressive sensing
Single-pixel imaging
Spectral-domain optical mixing

A B S T R A C T

In this letter a single-pixel imaging structure is proposed based on compressive sensing using a spatial light modulator (SLM)-based spectrum shaper. In the approach, an SLM-based spectrum shaper, the pattern of which is a predetermined pseudorandom bit sequence (PRBS), spectrally codes the optical pulse carrying image information. The energy of the spectrally mixed pulse is detected by a single-pixel photodiode and the measurement results are used to reconstruct the image via a sparse recovery algorithm. As the mixing of the image signal and the PRBS is performed in the spectral domain, optical pulse stretching, modulation, compression and synchronization in the time domain are avoided. Experiments are implemented to verify the feasibility of the approach.

1. Introduction

The ever-increasing amount of information places higher demands for the signal acquisition and processing technique, leading to the emergence of the compressive sensing (CS) theory [1–3], which provides a promising method of using fewer samples to represent the original signal. Realization of the CS with photonic techniques attracted an abundance of research interest due to the high bandwidth advantage of photonics. Multiple approaches to acquire a time-domain signal using photonic CS were proposed and demonstrated [4–14]. These include the compressively sampled photonic link [4,5], the photonic multi-channel CS [6,7], CS with the technique of photonic time stretch [8,9], photonic CS with improved mixing performance [10–12], CS with nanophotonic structures [13], and CS-based temporal channelization approach [14].

One of the significant applications of the CS theory is single-pixel imaging [15–24]. A key part of CS imaging is to implement the mixing of the image signal with a random pattern. A well-known method of realizing single-pixel imaging with CS is to use a digital micro-mirror device (DMD) in the system for optical mixing [15–17], in which the DMD is an array of tiny mirrors acting as the random mask. In this scheme, the image is projected onto the DMD array to complete the process of random mixing before the light is detected by a single-pixel photodiode. More recently, a technique based on the wavelength-dependent scattering of a single mode fiber to generate a random pattern for single-pixel imaging in place of the DMD was demonstrated in [18,19]. In [20,21] the technique of a coded aperture is employed to modulate the beams to realize the CS-based single-pixel imaging system, demonstrating that the observation model of the scheme with a coded aperture can be treated within the CS framework. Moreover, the technique of photonic time stretch of an ultrashort pulse is employed in single-pixel imaging schemes in order to increase the frame rate [22–24]. In these approaches, the pulse is first stretched by a coil of dispersive fiber and modulated by a random sequence in the time domain. Then the pulse is compressed by using another coil of fiber with conjugate dispersion to implement the time-domain compression before photodetection and signal processing. This kind of approach achieves high-speed imaging, as the high repetition rate of the optical pulsed laser is of the order of tens of megahertz.

In this letter, we present an approach for single-pixel imaging with spectral-domain mixing using an optical pulsed laser and spectrum shaper based on a spatial light modulator (SLM). In the approach, the image information is carried by the pulse spectrum through a grating-based imaging part and the random pattern is recorded on the SLM for mixing with the image information. In the imaging part, the pulse is dispersed by a diffraction grating and becomes a rainbow pulse, which illuminates the target object. The image information is projected onto the spectrum of the reflected pulse, which is then carved by the spectrum shaper. Benefitting from mixing in the spectral domain, we obviate the need for pulse stretch, compression and modulation in the time domain in comparison with these approaches based on photonic time

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http://dx.doi.org/10.1016/j.optcom.2017.05.057
Received 31 March 2017; Received in revised form 18 May 2017; Accepted 21 May 2017
0030-4018/

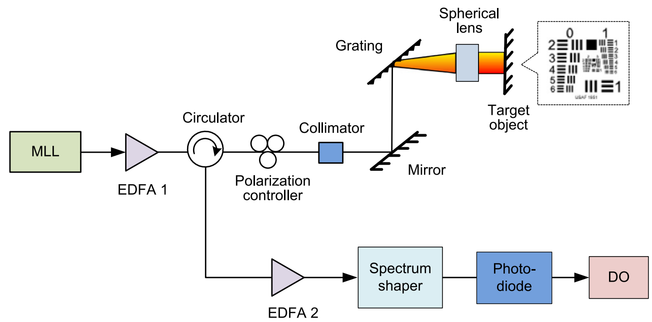

Fig. 1. Schematic illustration of the proposed single-pixel imaging system based on compressive sensing with spectral-domain optical mixing. MLL, mode locked laser; EDFA, erbium-doped fiber amplifier; DO, digital oscilloscope.

stretch [22–24]. Thus, we provide an alternative solution for single-pixel imaging in scenarios that do not need a high frame rate, such as the imaging of static objects and low-speed moving objects.

2. Principle

The CS algorithm aimed at recovering N samples of the input signal via M measurement results ($M \ll N$) by solving the optimization problem such as

$$\arg\min \|\mathbf{x}\|_{l_1} \quad \text{subject to } \mathbf{Ax} = \mathbf{y}, \tag{1}$$

where $\|\cdot\|_{l_1}$ denotes the l_1 norm function and $\mathbf{A}$ is the measurement matrix. The $M\times 1$ vector $\mathbf{y}$ denotes the compressed samples and the $N\times 1$ vector $\mathbf{x}$ denotes the signal to be recovered. As the $M \times N$ measurement matrix $\mathbf{A}$ and the measurement results $\mathbf{y}$ are known, the input signal can be reconstructed from the obtained results with a certain recovery algorithm such as the basis pursuit and orthogonal matching pursuit algorithm.

The schematic illustration of the proposed CS-based single-pixel imaging system with spectral-domain random mixing is shown in Fig. 1. In this scheme, the optical pulse is provided by a mode locked laser and amplified by an erbium-doped fiber amplifier (EDFA) to increase the power for the following imaging part. After passing through a three-port optical circulator and a polarization controller, the pulse enters the free space through a collimator and is reflected by a mirror. After dispersed by the diffraction grating, the pulse is mapped onto its spectrum in the spatial domain in one dimension, which realizes the function of wavelength-to-space mapping. The dispersed one dimensional rainbow pulse illuminates the target object through a spherical lens. When the pulse illuminates the target object, the image information is projected onto the spectrum of the pulse. The reflected pulse returns to the grating after passing through the spherical lens, which leads to the light recombining in the spatial domain. This process is equivalent to the function of integration. The reflected pulse re-enters the circulator with the spectrum being shaped by the object after passing through the grating, the mirror, the collimator and the polarization controller. The second EDFA amplifies the power of the pulse which carries the image information on its spectrum. A spectrum shaper with an SLM codes the spectrum of the input pulse using a predefined random sequence, which realizes the mixing function of the signal and the pseudorandom bit sequence (PRBS) in the spectral domain. Since the energy of the pulse represents the inner product of the image signal and the random pattern, the spectrally mixed signal is detected by a single-pixel photodiode and the peak value is captured by a digital oscilloscope. With the help of the recovery algorithm, each line of the target image can be reconstructed.

In our scheme, the measurement process can be modeled as

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_M \end{bmatrix} = \begin{bmatrix} \mathbf{A}_1 \\ \mathbf{A}_2 \\ \vdots \\ \mathbf{A}_M \end{bmatrix} \mathbf{x}_l, \tag{2}$$

where y_m ($m = 1, 2, \ldots, M$) denotes the measured result obtained by the digital oscilloscope, $\mathbf{A}_m$ ($m = 1, 2, \ldots, M$) is a $1 \times N$ vector representing the mth measurement process and $\mathbf{x}_l$ ($l = 1, 2, \ldots, L$) is a $N \times 1$ vector representing the lth horizontal line of the image, assuming that the size of the target image is $L \times N$ pixels. Each random sequence is N bits and it is recorded on the spectrum of the pulse. For each horizontal line of the image, there are independent M measurements, which means there are M random sequences denoted by $\mathbf{A}$ and M measurement results denoted by $\mathbf{y}$. The $1\times N$ vector $\mathbf{A}_m$ represents the N-bit random sequence and the integration function. With the measurement matrix $\mathbf{A}$ and the measurement result $\mathbf{y}$, we can reconstruct every line of the image by solving the problem

$$\arg\min \|\mathbf{x}\|_{TV} \quad \text{subject to } \|\mathbf{Ax} - \mathbf{y}\|_2 \le \varepsilon, \tag{3}$$

where the total variation (TV) norm is defined as the summed magnitude of the spatial gradient [18] and ε is a parameter denoting a small error term, which relates to the noise in the measurement process.

Note that in our single-pixel imaging scheme, the mixing of the signal and the PRBS, which is required in the CS, is realized in the spectral domain instead of the time domain using the SLM-based spectrum shaper. The PRBS is set in the programmable SLM according to the predefined sequence, which carves the spectrum of the input optical pulse. In the schemes the mixing function is performed in the time domain as in [22–24], the optical pulse needs to be stretched by a length of dispersive fiber to perform wavelength-to-time mapping at first, and the stretched pulse is then modulated by a random sequence with a Mach–Zehnder modulator in the time domain. To compress the stretched pulse, another coil of single mode fiber with conjugate dispersion should be used before the pulse is detected by a photodiode to implement O/E conversion. These approaches require stringent time-domain synchronization between the pulses and the random sequences, which is usually implemented by splitting the optical pulse via a coupler and treating one way of the split pulses as a trigger signal for the pulse pattern generator. Compared with the schemes performing the time-domain mixing, our scheme realizes the mixing directly in the spectral domain, which does not need a pair of conjugate dispersion media, a high-speed programmable pattern generator and a Mach–Zehnder modulator. Furthermore, complicated time-domain synchronization between the pulsed laser and the pattern generator is also avoided. In this sense our proposed approach remarkably simplifies the system. Limited to the updating speed of the SLM in the spectrum shaper, the presented scheme can be used in the scenarios with a relatively low requirement of speed.

3. Experimental results

An experiment with the setup shown in Fig. 1 is implemented. The optical pulses are provided by the mode locked laser with a repetition rate of 24.91 MHz, a center wavelength of 1545 nm and a pulse width of 300 fs. The first EDFA is to amplify the pulses at an average output power of about 15.4 dBm. A diffraction grating with 600 lines per mm is used to disperse the pulse and a spherical lens with a focal length of 50.8 mm is used to focus the light to a spot with length of about 1.2 mm and width less than 0.1 mm. We use a 2.5 cm × 2.5 cm USAF-1951 standard resolution chart as the test target. The second EDFA is used to compensate the power attenuation in the imaging system, with a power gain around 5 dB. The SLM-based spectrum shaper (Finisar Waveshaper 1000S) is set according to different PRBSs with length of 50, which are prepared offline using a MATLAB program. The spectral width of 20 nm of the pulse is used in our experiment, which is also the bandwidth of the spectrum shaper. A photodiode with a bandwidth of 10 GHz is used to detect the signal and the peak value of each pulse is captured by the oscilloscope.

Two typical spectra of the reflected pulses after illuminating the test target are shown in Fig. 2(a) and (b). In this case the spectrum shaper is set to the 'all pass' state. From Fig. 2(a) and (b), we can clearly see that