Optics Communications 352 (2015) 45–48

Contents lists available at ScienceDirect

Optics Communications

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

Compressed spectral imaging with a spectrometer

Chao Wang [a,b], Xue-Feng Liu [b,*], Wen-Kai Yu [b,c], Xu-Ri Yao [b,c], Long-Zhen Li [b,c], Qing Zhao [a], Guang-Jie Zhai [b]

[a] College of Physics, Beijing Institute of Technology, 100081, China
[b] Key Laboratory of Electronics and Information Technology for Space Systems, Center for Space Science and Applied Research, Chinese Academy of Sciences, Beijing 100190, China
[c] University of Chinese Academy of Sciences, Beijing 100190, China

ARTICLE INFO

Article history:
Received 16 February 2015
Received in revised form
27 April 2015
Accepted 29 April 2015
Available online 2 May 2015

Keywords:
Spectral imaging
Compressed sensing
Spectrometer
Spatial resolution
Spectral resolution

ABSTRACT

We report an experimental demonstration of spectral imaging with a spectrometer without any scanning. The spatial resolution is provided by spatial light modulation based on the theory of compressed sensing. Objects with both continuous and discrete spectrum are used to demonstrate the performance of our system, which shows wide-spectrum and high efficient spectral imaging ability. The spatial and spectral resolutions of our imaging system are also discussed.

1. Introduction

Spectrometer is a fundamental instrument in basic and applied optical research. As spectroscopic analysis can provide the component and structure information of matters, spectrum detection is of great importance in many fields, such as biology [1], material analysis [2], and astronomical research [3]. In recent years, spectral imaging attracts much attention as a new technology in which spectral and spatial information are both obtained, giving more benefits for matter analysis [4–7]. Imaging spectrometers emerge frequently in airborne and satellite borne instruments for remote sensing and astronomical observation [8–10]. However, traditional spectral measurement approach cannot give spectral information of multi-points in the object simultaneously. As a substitute, in most current imaging spectrometers the spatial information is obtained by scanning the object point by point. This unavoidably brings mechanical movement in the equipment, causing instability and time wasting.

Recently a new sampling theory called compressed sensing (CS) was derived, which mathematically proves that signal can be perfectly reconstructed from linear measurements with sampling number less than requirement of Nyquist–Shannon theorem [11–13]. In 2008, Baraniuk et al. proposed an imaging technique based on CS, which only used a point detector without spatial resolution to achieve two-dimensional imaging and so was named as single pixel camera [14–16]. Since it was derived, single pixel camera has been widely used in many fields, such as remote sensing, quantum physics and single photon imaging [17–19]. CS has also been applied in spectral imaging [20–23], in which a two-dimensional array detector is used to obtain spectral image of an object.

In this paper, we combine the single pixel camera and traditional spectral detection to achieve spectral imaging with a spectrometer, which means a linear array detector. During the imaging process mechanical scanning is needless and sampling number is dramatically saved.

2. Theory and experiments

Compressed sensing is a sampling theory which does not measure the target signal directly. Supposing x is the original signal with p elements, we measure the scalar product of the signal and a measurement matrix A with size $q \times p$:

$$y = Ax + e, \tag{1}$$

where y is the measurement result and e the noise. If the measurement number q is less than the element number p, Eq. (1) is underdetermined and a unique solution cannot be obtained.

* Corresponding author. Fax: +86 10 62586492.
E-mail addresses: liuxuefeng@nssc.ac.cn (X.-F. Liu), qzhaoyuping@bit.edu.cn (Q. Zhao).

http://dx.doi.org/10.1016/j.optcom.2015.04.081
0030-4018/

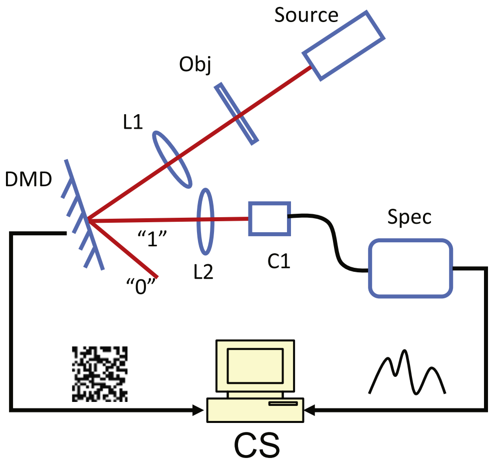

Fig. 1. Experimental setup of spectral imaging with a spectrometer. Obj, object; L1, L2, lens; C1, fiber collimator; Spec, spectrometer. The distances from L1 to object and DMD are 12.5 cm and 8.5 cm, respectively. The distances from L2 to DMD and C1 are 8.5 cm and 10.5 cm, respectively.

However, CS theory proves if two conditions are satisfied, the original signal x can be accurately solved. First, the signal x must be sparse, or sparse under certain basis such as wavelets. Second, the measurement matrix A must obey RIP restriction, which indicates that a random matrix is proper in almost all situations. Under these conditions, the signal x can be reconstructed by solving the following optimization problem:

$$\min_x \frac{1}{2} \|y - Ax\|_2^2 + \tau \|x\|_1, \quad (2)$$

where τ is a parameter weighting the two terms in Eq. (2) which indicate the consistencies of solution with measurement results and prior knowledge of sparse, respectively, and $\|\cdots\|_p$ stands for l_p norm, defined as $\left(\|x\|_p\right)^p = \sum_{i=1}^{N} |x_i|^p$. For a signal with sparsity k which means only k elements are significantly nonzero, it is mathematically proved that the signal can be accurately reconstructed with $q \geq Ck\log(n/k)$ measurements, in which n is the number of elements and C a constant coefficient [13,24].

The spectral imaging setup is shown in Fig. 1. Light from a halogen lamp with collimated fiber output illuminates the object, which is then imaged onto the digital micromirror device (DMD) by the lens L1. The DMD consists of 1024 × 768 micro-mirrors each of size 13.68 μm × 13.68 μm which independently reflect the light to two directions "0" and "1", according to 0–1 random matrix loaded into the DMD. The focal length of L1 is 50.8 mm and the magnification of the image is 0.68. A lens L2 with focal length of 50.8 mm is placed on the "1" direction, collecting light from parts of the image with position coordinates corresponding to 1 in the matrix to the fiber collimator C1, which has an aperture of 5 mm and focal length of 18 mm. The collimator focuses the light into a fiber with core diameter of 200 μm placed on the focal plane of C1. The light is then transferred to a traditional spectrometer to measure the spectrum. In the experiment, N random patterns composing the measurement matrix A will be fed into the DMD, making different parts of the object be collected, and N correspondent spectrum lines y are given by the spectrometer. The random matrix A and spectrum y make up linear equations like Eq. (1):

$$y(\lambda) = A(x)t(x, \lambda), \quad (3)$$

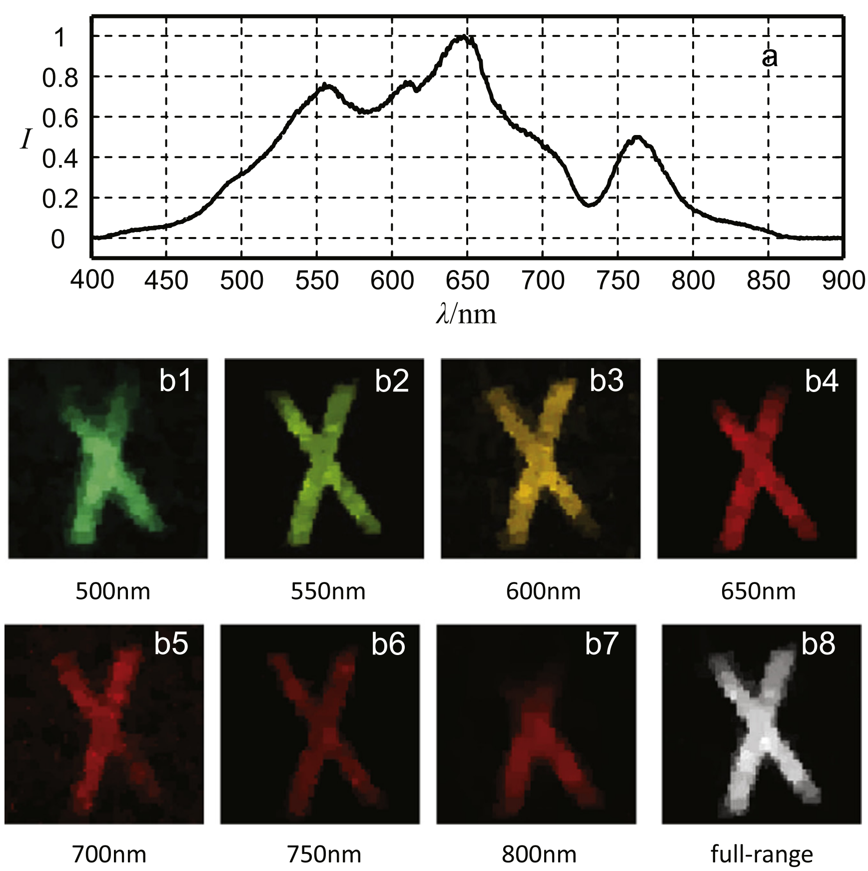

Fig. 2. Spectral imaging result of a continuous full-spectral-range object. (a) Transmission spectrum of the object. (b1)–(b7) Imaging results of different wavelengths. (b8) Imaging result of full-range wavelength. For clear vision the reconstructed grey images are shown with colors corresponding to the wavelengths. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)