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Large aperture spatial heterodyne imaging spectrometer: Principle and experimental results

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ABSTRACT

A large aperture spatial heterodyne imaging spectrometer (LASHIS) is proposed. It is a kind of pushbroom Fourier transform ultraspectral imager with no moving parts. This imaging spectrometer, based on a Sagnac lateral shearing interferometer combined with a pair of gratings, has the advantages of high spectral resolution, high throughput and robustness. The principle of LASHIS and its spectral retrieval method are introduced. The processing chain to convert raw images to ultraspectral datacube is also described. Experimental results demonstrate the high resolving power of LASHIS with the emission spectrum of a low pressure sodium lamp.

1. Introduction

In the Fourier transform spectroscopy (FTS), the spectral resolution is determined by the maximum optical path difference (OPD). According to the Nyquist theorem, the sampling points of the interferogram must be matched to the maximum wavenumber of the input spectrum [1]. The spatial heterodyne spectroscopy (SHS) can dramatically reduce the sampling points by heterodyning the frequency of the interferogram about a selected reference wavenumber [2]. For SHS, the number of sampling points is proportional to the bandwidth of the input spectrum [3]. Thus, SHS can get a very high resolving power over a relatively narrow spectral band. The first practical spatial heterodyne spectrometer was invented by Roesler and Harlander [4,5]. Their basic SHS configuration is based on a Michelson interferometer modified by replacing the mirrors in each arm with diffraction gratings. Recently, Harlander and Englert et al. have developed a Doppler asymmetric spatial heterodyne (DASH) spectroscopy technique for upper atmospheric wind and temperature observations [6,7]. It is a variation of SHS with an asymmetric OPD and has a higher resolving power than SHS.

The large aperture static imaging spectrometer (LASIS) [8] proposed by the author is a high throughput static Fourier transform spectral imager. It has been launched in 2010 and achieved hyperspectral datacubes. Some schemes with large aperture have also been proposed in recent teens of years [9–11]. The optical layout and principle of LASIS are shown in Fig. 1. It is an imaging system combined with a Sagnac lateral shearing interferometer. LASIS is a true imaging spectrometer which images the scene onto a 2D detector superimposed with interference fringes. Thus, one frame of the images contains not only the two dimensional spatial information but also the interference information. By scanning across the scene in the direction perpendicular to the interference fringes, the interferogram of one point could be extracted from a sequence of images containing the interference information of this point [12,13]. It is a temporally-spatially combined modulated spectrometer. The primary merits of LASIS are the high throughput and stability.

In this paper, a large aperture spatial heterodyne imaging spectrometer (LASHIS) in heritages of both SHS and LASIS is presented. It has high resolving power, high throughput and no moving parts. The high resolving power is achieved by introducing a pair of matched parallel gratings into the Sagnac lateral shearing interferometer and producing heterodyned interference fringes superimposed on the image (as shown in Fig. 5). The high throughput is obtained because there is no entrance slit, and it is a LASIS if the grating pair is removed. These advantages make LASHIS particularly suitable for faint fine spectrum detection. In the following parts, the principle of LASHIS is elaborated in Section 2.

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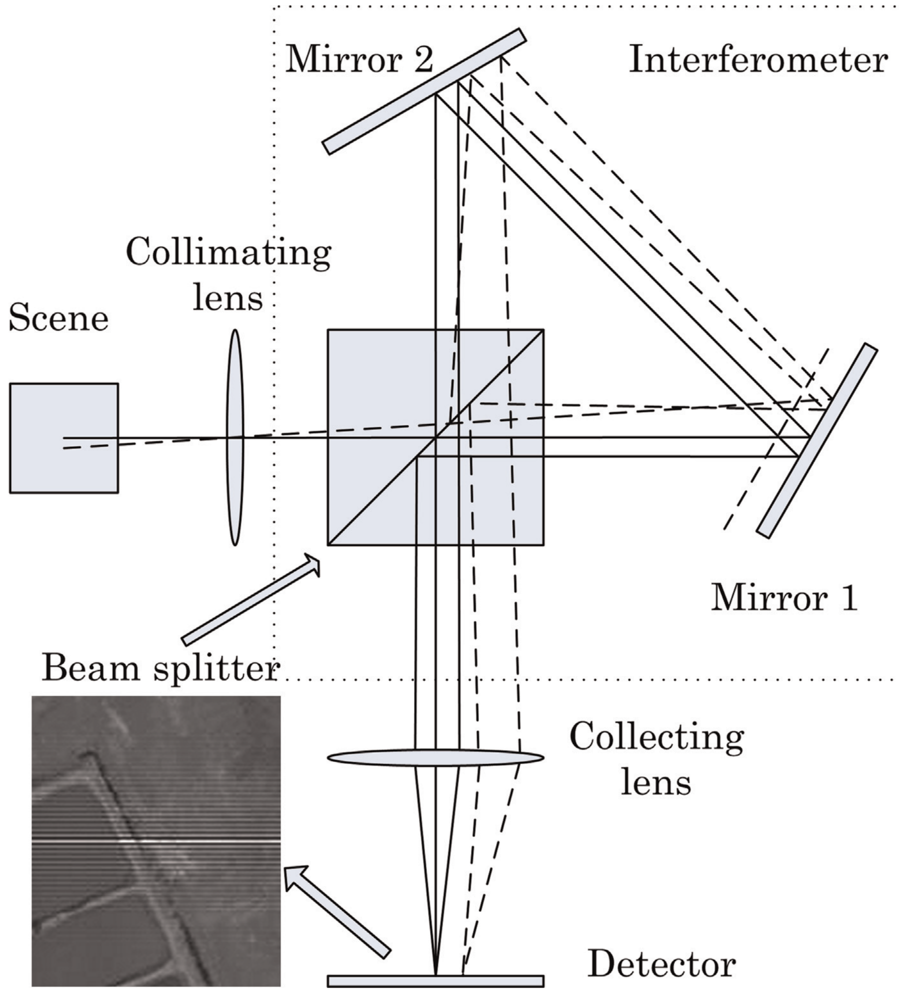

Fig. 1. Optical layout and principle of LASIS. The collimating lens gathers light from each point of the scene and collimates it into the Sagnac lateral shearing interferometer. The interferometer splits incident source into two portions. Then, the collecting lens images the scene onto detector superimposed with interference fringes. The solid and dashed lines show the rays from different points passing through LASIS. As OPD varies with the field angle, the image is superimposed with interference fringes.

A design example and the experimental results with the emission spectrum of a low pressure sodium lamp are presented in Section 3. Conclusions are drawn in Section 4.

2. Principle of LASHIS

The sketch of the optical layout of LASHIS is shown in Fig. 2. It consists of a collimating lens, a Sagnac lateral shearing interferometer, a pair of gratings, a collecting lens and a detector. The collimating lens gathers light from each point of the scene and collimates it into the interferometer. The interferometer is modified by introducing a pair of matched parallel gratings into the Sagnac interferometer. This modified interferometer splits the incident source into two portions: a transmitted portion and a reflected portion. The detector is placed at the focal plane of the collecting lens, and the collecting lens images the scene onto detector. Same as LASIS, different points of the scene are imaged onto different pixels with different OPDs. The recorded image is superimposed with interference fringes.

There is an obvious difference between Sagnac interferometer and the modified interferometer in LASHIS. In Sagnac interferometer, the lateral displacement of the two virtual sources is fixed. While in LASHIS, it varies with wavenumber because of the dispersion of the parallel gratings. This is illustrated in Fig. 2. For the on-axis rays, after split by the modified interferometer, the blue beam (dot dash line) has a wider separation than the red beam (dash line). Because of the wavenumber dependent lateral displacement, the frequency of the interferogram of LASHIS can be heterodyned to a selected wavenumber whose lateral displacement is zero. This character makes LASHIS capable of very high spectral resolution in a selected bandwidth [14]. The heterodyned interferogram generated in LASHIS can be understood in Fig. 3 where a blue light source and a red light source are illustrated. The gratings diffract the blue beam more than the red beam, yielding a wider separation of virtual sources $S1_{\mathrm{blue}}$ and $S2_{\mathrm{blue}}$, and a closer separation of $S1_{\mathrm{red}}$ and $S2_{\mathrm{red}}$. The interferograms of these two sources can be generated by scanning the entire field of view. As their different separations, the corresponding frequency of the interferogram for the red source is lower than the blue one. For a particular wavenumber whose separation is zero, it produces an interferogram with zero frequency. This is the heterodyned wavenumber.

In order to determine the heterodyned interferogram generated by LASHIS, the lateral displacement of the two virtual sources should be calculated first. Fig. 4 shows the reflected beams diffracted by the grating pair. As the two gratings are parallel with each other, the exiting rays and the incident rays have the same direction. The light diffracted by the two parallel gratings has a displacement $h(\nu)$ inversely proportional to the wavenumber. That is