Fabry–Pérot Interferometer-Based Tunable Narrow-Band Imager for Solar Chromospheric Observation: First Results

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Abstract
Recently, we have developed a tunable narrow-band imager (NBI) with high spectral resolution based on a Fabry–Pérot (FP) interferometer to observe the solar chromosphere. The NBI system is designed for imaging the Sun at the Hα wavelength (6563 Å). The FP interferometer has a bandpass (FWHM) of 0.09 Å and a free spectral range (FSR) of 3.85 Å at λ = 628 nm, working in combination with a prefilter with a bandpass of 1.6 Å and a center wavelength at 656.3 nm to achieve narrow-band imaging. We have successfully tested the NBI system on the 65-cm Educational Adaptive-optics Solar Telescope (EAST) in the Shanghai Astronomy Museum, and observed the sunspots in active region (AR) 12880 of the Sun on October 2 and 3, 2021. In this paper, we briefly present a description of the instrument, experimental observations, data processing, and the first observational results.

Keywords Chromosphere, active · Active regions · Sunspots · Spectrum

1. Introduction

The chromosphere is an important layer of the solar atmosphere and it is not very well understood as yet. To study the fine structure, temporal evolution, and the dynamics of features at the chromospheric level, high spectral resolution, high spatial and temporal resolution imaging spectroscopy is needed (Chae et al., 2013). Imaging spectroscopy can be achieved by either a high-resolution spectrograph or a tunable narrow-band filter. There are many advantages and disadvantages with the two types of instrument. Instruments based on a spectrograph can have a high spectral resolution, but spatial scanning is required to obtain two-dimensional (2D) solar images; Using a tunable narrow-band filter one can obtain 2D images, but it must scan multiple wavelength positions to reconstruct the spectra (Dhara, Ravindra, and Banyal, 2016; Gosain, Venkatakrishnan, and Venugopalan, 2004; Choudhary, Yurchyshyn, and Gosain, 2013).
A Fabry–Pérot interferometer (FPI) is a powerful instrument for narrow-band imaging in solar astronomy. A FPI-based imaging system has a high light throughput and transmittance, as a result the imaging time periods can be very short at each scanning position and one can scan across the spectral lines rapidly (Dhara, Ravindra, and Banyal, 2016). An imaging spectrometer can have simultaneously high spectral, spatial, and temporal resolution using FPI, and the spectral resolution can be further improved when multi-FPIs are used (Cavallini, 2006). Today’s advanced ground-based solar telescopes are regularly equipped with a FPI-based imaging spectrometer for tunable narrow-band imaging (Cavallini, 2006; Ravindra and Banyal, 2010; Puschmann et al., 2013). A benefit from the large aperture of the telescope (Rao et al., 2020), adaptive optics (AO) (Rao et al., 2016b,a, 2010), and postfacto image-processing techniques (Zhong, Tian, and Rao, 2014), is that more details of the features in the solar atmosphere can be studied.

Recently, we have developed an FPI based narrow-band imager for observing the solar chromosphere. We use a single FPI working in combination with a prefilter to achieve narrow-band imaging. We have successfully tested the NBI system on the 65-cm Educational Adaptive-optics Solar Telescope (EAST) (Rao et al., 2022) in the Shanghai Astronomy Museum, and conducted the observation experiment.

In Section 2, we give some details of the instrument. In Section 3, we describe the observation experiment. In Section 4, we discuss our data-processing procedure and present the first observational results. Finally in Section 5, we summarize our work presented in this paper as well as propose the research work to be carried out in the next phase.

2. The Instrument

2.1. Optical Layout

The optical layout of the NBI system is shown in Figure 1. The beam from the AO system is reduced to match the aperture of the prefilter and FPI. The FPI works in combination with the prefilter to achieve narrow-band imaging, and a CCD camera is used as the imaging detector. We also developed software to control the cavity spacing between the two plates of the FPI and the image capturing of the camera. The scanning process across the spectral-line profile can be finished automatically after the experimental parameters including the wavelength position to be sampled, exposure time of the camera, and the number of frames to be captured in each wavelength are set up.
2.2. The FPI etalon

An FPI consists of two plane plates thinly silvered on the inner surfaces. Based on the principle of interference involving multiple reflections (Jenkins and White, 2001), this instrument reinforces the intensity of transmitted rays that satisfy the condition

\[ 2nd \cos \theta = m\lambda, \]  

where \( n \) is the refractive index of the film between the two plates, \( d \) is the thickness of the film, \( m \) is the order of interference, \( \theta \) is the angle of incidence, and \( \lambda \) is the wavelength of incident light. The intensity distribution of the transmitted beam is given by Airy’s formula:

\[ I = \frac{I_{\text{max}}}{1 + F \sin^2 \left( \frac{\delta}{2} \right)} \]  

\[ I_{\text{max}} = \frac{A^2 T^2}{(1 - R)^2} \]  

\[ F = \frac{4R}{(1 - R)^2} \]  

\[ \delta = \frac{4\pi nd \cos \theta}{\lambda}, \]  

where \( I_{\text{max}} \) is the maximum value of the intensity, \( F \) is the reflective finesse, \( A \) is the amplitude of the incident light, \( T \) and \( R \) are the transmitivity and reflectivity of the FPI etalon surface, respectively, and \( \delta \) is the phase difference between multiple transmitted rays after subsequent cavity reflections.

There are two parameters that characterize the performance of a FP etalon, (1) the finesse and (2) the free spectral range (FSR) (Ravindra and Banyal, 2010; Dhara, Ravindra, and Banyal, 2016). The finesse is the ratio between the distance of two neighboring peaks and their half-width. FSR is the wavelength distance between two adjacent maxima and is given by

\[ \text{FSR} = \frac{\lambda^2}{2nd \cos \theta}. \]  

The passband (FWHM) of the FP can be estimated from the finesse and the FSR by the relation

\[ \text{FWHM} = \frac{\text{FSR}}{F}. \]  

Our FPI (ET100 etalon) and its controller CS100 was manufactured by IC Optical Systems Ltd, the specifications of the FPI provided by the vendor are listed in Table 1.

We also calibrated our FP etalon in the laboratory with a He-Ne laser. The transmitted intensity of the laser beam through the FP etalon was measured as the cavity spacing between the two plates was varied. The calibrated results are shown in Figure 2. According to our calibrated results, the FSR of the FP etalon is about 3.85 Å, and the FWHM of each transmission peaks is about 0.09 Å.
Table 1  Specifications of the FP etalon.

| Parameter                        | Value                  |
|----------------------------------|------------------------|
| Cavity length                    | 562 µm                 |
| Range of cavity-length adjustment| ±2.72 µm               |
| Clear aperture diameter          | 104.96 mm              |
| Surface flatness                 | λ/168 at 632.8 nm      |
| FSR                              | 3.56 Å at 632.8 nm     |
| FWHM                             | 0.0775 Å at 632.8 nm   |
| Peak transmittance               | 82.2%                  |
| Scan resolution                  | 1.7 mÅ                 |

Figure 2  The transmitted intensity of the laser beam as the cavity spacing between the two plates was varied. The red dots indicate the measured intensity, and the black solid line indicates the profile fitted with Airy’s function.

2.3. The prefilter

The ideal prefilter should suppress all transmission peaks of FPI except the one near the center wavelength of the prefilter when the cavity spacing between the two plates is varied. Hence, the designed bandpass of the prefilter should be less than half of the FSR of the FPI. Since the tuning range of the narrow-band imaging is also determined by the bandpass of the prefilter, the designed bandpass of the filter should not be too narrow. The FSR of our FP etalon is 3.85 Å, according to the design principle, the bandpass of the prefilter is preferred to be nearly 1.9 Å.

Our prefilter consists of a tunable 3-stage field-widened designed Lyot filter and a narrow-bandpass interference filter. The prefilter was manufactured by the Nanjing Institute of Astronomical Optics and Technology, the Chinese Academy of Sciences. The prefilter was also calibrated by the manufacturer using their spectrograph. Figure 3 shows the calibrated transmission function of the prefilter, which is plotted from the calibrated data given by our manufacturer, and the specifications of the prefilter are listed in Table 2.
Figure 3 The calibrated transmission function of the prefilter, the red dots indicate the calibrated intensity and the black solid line indicates the profile fitted with a Gaussian curve.

![Figure 3](image)

Table 2 Specifications of the prefilter.

| Parameter             | Value          |
|-----------------------|----------------|
| Type                  | Interference + Lyot |
| FWHM                  | 1.6 Å          |
| Center wavelength     | 6562.7 Å       |
| Peak transmittance    | >70%           |
| Working temperature   | 42 °C          |
| Temperature stability | ±0.01 °C       |

3. The Observational Experiment

The NBI system has been successfully mounted on the 65-cm Educational Adaptive-optics Solar Telescope solar telescope in the Shanghai Astronomy Museum, and the observational experiment was conducted on October 2 and 3, 2021, following the procedure described below.

First, we calibrated the tuning position of the FPI that aligning a transmission maximum to the Hα core wavelength (6562.8 Å). The Hα line profile in the quiet region of the Sun was scanned, as shown in Figure 4, the intensity was measured by the camera while scanning across the Hα line profile. Compared with the theoretical intensity profile, the calibrated curve has a lower contrast. We can infer that the passband of the FP is not ideally narrow and there is also some stray light.

After the calibration, several wavelength positions of Hα line profile to be sampled were set in the control software, and the flat and dark images at each wavelength were captured.

Finally, we aimed the telescope at active region (AR) 12880 of the Sun and captured the images of the sunspots at nine different wavelength positions across the Hα line profile (from −0.384 Å to +0.640 Å). The filtergrams at each sampled wavelength position are shown in Figure 5.

The exposure time was set to 20 ms, and 20 frames of the image in each wavelength position were taken, the complete scanning could be finished in about 10 s. The observational results are presented in Section 4.
4. Data Processing and First Results

The images were processed after the observational experiment. Each frame was processed with the flat and dark correction first, then a Wiener filter was used to deconvolute the frames with the point spread function (PSF) of the NBI system, which was measured by a point source. Finally, an image-restoration process based on frame selection and multiframes blind deconvolution (Yu, Chang-hui, and Kai, 2009) was applied to the frames. One frame of the object imaged at each wavelength was obtained after the processing. Figure 6 shows an example of the image-processing procedure and Figure 7 shows the processed images of each sampled wavelength position.

5. Summary

In this paper, we briefly describe the NBI system that can image the solar chromosphere at different wavelength across the Hα line profile. According to the parameters of the instru-
Figure 6  Example of the image-processing procedure. Raw image (left upper), image after dark and flat correction (right upper), image after static aberration deconvolution (left lower), image after multiframes blind deconvolution (right lower).

Figure 7  The processed images of each sampled wavelength position (AR 12880, UTC 2021-10-02T05:08:24).
ments and our observational results, the specifications of the NBI system are summarized in Table 3.

The developed NBI system has a high spectral resolution and a high temporal resolution, and the spatial resolution can be improved when working in combination with a telescope with a larger aperture. There are also some shortcomings of the developed NBI system. Since the bandpass of the prefilter is very narrow, the wavelength-tuning range is limited. According to our observational experiment, there is also some stray light that enters into the imaging system.

In the future, we will mount the instrument on the Chinese Large Solar Telescope (CLST) (Rao et al., 2016c) with a 1.8-m aperture for observations with higher spatial resolution as well as move the prefilter into other center wavelengths to study the features at different levels of the solar atmosphere. We also will consider developing a multi-FPI-based NBI, which can achieve a higher spectral resolution and a larger wavelength-tuning range.

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Declarations

Disclosure of Potential Conflicts of Interest The authors declare that they have no conflicts of interest.

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