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Flare Sentinel - A Compact Integral Field Spectrograph for Observations of Solar Flares from Space

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ABSTRACT

This paper describes Flare Sentinel, a compact integral field spectrograph (IFS) for the study of the hydrogen Balmer series spectrum from 350 to 450 nm of solar flare from space. Flare Sentinel IFS is based on a new Machined Image Slicer Compact Spectrograph Array (MICS) design. MICS consists of an image slicer that divides a continuous 2D spatial field formed by an imaging system into multiple narrow slices, and an array of miniature spectrographs, each forming the spectra of one of the slices of the 2D field. The spectra formed by all the miniature spectrographs can be projected on a common 2D focal plane to be recorded by an image sensors. The spectra can also be distributed to multiple focal planes and recorded simultaneously by multiple sensors to increase the instantaneous hyperspectral field of view of the instrument. New image slicers with slit width of 36 um and 20 um have been successfully fabricated using Canon Inc.'s ultra-precision diamond-cutting CNC mill. This capability is enabling design and fabrication of IFSs with imaging format of $10^2 \times 10^2$, and spectral resolution between $100 < R < 10,000$ in a very compact package. We will present the optical design and the optical hardware of a prototype IFS that has been fabricated.

Keywords: Image Slicer, Integral Field Unit, Integral Field Spectrograph, Solar Spectroscopy, Solar Flares

1. INTRODUCTION

Solar flares are sudden brightening of the solar surface, most easily observed in narrow band images of the hydrogen Hα 656.3 nm line that originate from the chromosphere. The enhanced brightness of the most powerful flares (white light flares) can be seen in the continuum images of the sun, and the energy released in super stellar flares can outshine the stars. Flares are dynamic reconfiguration of the magnetic fields in the solar atmosphere that result in the heating of the atmosphere and ejection of high energy particles into the interstellar space. However, the exact physical condition(s) that can trigger the flares, the mechanisms that heat the atmosphere and accelerates the particles are still not well understood, making them unpredictable.

Resolving the physics of flares requires comprehensive knowledge of the magnetic and thermodynamics properties of the solar atmosphere before, during, and after flares, and observations of the hydrogen Balmer series spectral lines is one of the most powerful tools of the study of the thermodynamics of flares.[1] On the sun, flares are seen in active regions containing sunspots with irregular shape, and the brightening occurs over an extended area comparable to the size of the active regions. Additionally, brightening occurs in burst in small, arcsecond-sized flare kernels, as well as extended flare 'ribbons'. Due to the unpredictable nature of flares, conventional scanning slit spectrographs often failed to capture the important impulsive phase of flares. On the other hand, imaging spectrometers based on tunable filters cannot provide the simultaneous spectral coverage over extended spectral window. Most importantly, neither can deliver the hyperspetral data cube with the high temporal resolution needed to resolve the dynamic time scale of flares. Thus spectroscopic observation of solar flares require integral field spectrograph (IFS) with large spatial and spectral field of view (FOV) coverage (the *hyperspectral field of view*), 'good' spatial and spectral resolution, and most importantly, with high temporal resolution in the orders of seconds or less.

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Conventional Integral Field Spectrographs are composed of two parts: 1) an Integral Field Unit (IFU) that reformats a 2D spatial field into long narrow slices, and 2) a conventional grating spectrograph coupled with a 2D sensor to record the spectra of all of the the field points simultaneously. Three types of IFUs, namely, 1) microlens arrays, 2) coherent fiber optic arrays, and 3) machined or polished glass image slicers are commonly used for the construction of IFSs, each with their advantages and limitations. The Diffraction-Limited Near-IR Spectropolarimeter (DL-NIRSP)[2] of the Daniel K. Inouye Solar Telescope (DKIST)[3] equipped with two very specialized Birefringent Fiber-Optic Image Slicers (BiFOISs),[4] and the Gregor Infrared Spectrograph (GRIS)[5] equipped with a polished glass image slicer are two recent examples of IFS for solar observations. The optical systems of the spectrographs of conventional IFS are usually large due to the need to support the extended long slit formed by the IFUs. The multi-slit format of the DL-NIRSP IFUs require the spectrograph to support a 36 mm $\times$ 36 mm 2D entrance slit plane further exacerbates the problem. Due to the large spectrographs, the intrinsic spectral resolution these spectrographs (limited by the illuminated size of the grating) can achieve usually far exceeds the resolution required for the experiments.

In this paper, we describe the conceptual design for Flare Sentinel, a proof-of-concept instrument for flare spectroscopy of hydrogen Balmer series spectral lines based on a new flexible and scalable machined image slicer compact spectrograph (MICS) design. MICS is a compact spectrograph consists of a machined image slicer, followed by an array of small spectrographs with one spectrograph for each slicer mirror. This design eliminates the need for a large conventional slit spectrograph allowing us to greatly reduce the size of the instrument. The following sections describe the optical desing of MICS, and two conceptual designs of Flare Sentinel, one with a single MICS, and one with four MICS to demonstrate the flexibility and scalability of this new IFS design.

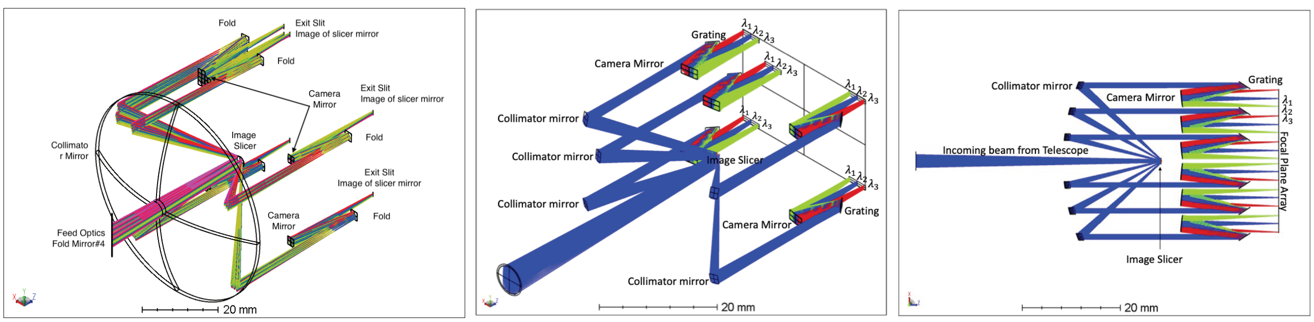

Figure 1. Left: Isometric view of the optical system of MISI-36 IFU. Only the ray traces of 6 out of the 112 micro slicer mirrors are shown to better illustrate the optical configuration of the IFU. Middle: The optical system of a 96-slit MICS. Right: MICS optical system viewed from the top.

2. FLARE SENTINEL

2.1 The Machined Image Slicer Compact Spectrograph

The machined image slicer compact spectrograph is a new integral field spectrograph deesign derived from the 36 μm four-mirror machined image slicer IFU (MISI-36),[6] a drop-in upgrade for the 36-um slit BiFOIS of DL-NIRSP. This design is enabled by the ultra-precision diamond cutting optics fabrication capabilities developed by Canon Inc., which enables the fabrication of micro optics with feature size of 10s of μm or less.[7] The Zemax model of the optical system of MISI-36 is reproduced in the left panel of Figure 1. MISI-36 utilizes a 4-mirror (a micro slicer mirror, a collimator, a fold mirror, and a reimaging camera mirror) reimaging system to rearrange the narrow telescope subfields sampled by each of the micro slicer mirrors into four long (staggered) virtual slits. Two simple modifications are made to transform the 4-mirror IFU into a compact IFS in the form of a miniature spectrograph array (mSGA) as shown in the middle panel of Figure 1. First, MICS replaces the common parabolic collimator mirror with individual off-axis parabolic mirrors (OAPs) to collimate the beams reflected by the micro slicer mirrors. Second, the fold mirrors of MISI-36 are replaced with plane reflecting gratings, turning the 4-mirror reimaging systems into miniature grating spectrographs. The apex of the OAPs are placed at the center of the slicer mirrors. Therefore, the beams reflected off the collimators are all parallel with respect to each others, as shown in the right panel of Figure 1. All miniature spectrographs have identical gratings with the same groove density and blazing angle and are configured with identical grating α angle and spectrograph angle $\psi = \alpha - \beta$, where α is the incident angle of the beam with respect to the grating normal, and β is the exit angle of the diffracted beam with respect to the grating normal.

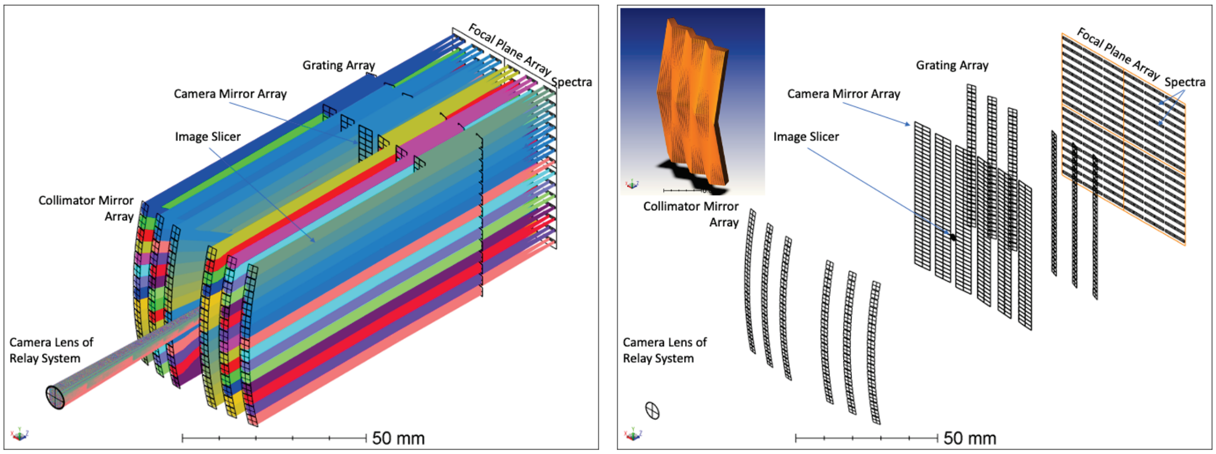

Figure 2. Left: Isometric view of an example 54-slit MICS IFS with full ray trace. Right: MICS IFS without ray trace to show the optical components more clearly. Details of the split image slicer is shown in the upper left-hand-corner insert. The width of the slicer mirrors is 20 μm. This IFS contains a total of 84 mini spectrographs.

2.2 Flare Sentinel IFS Prototype

Figure 2 shows the full optical model of an example 54-slit IFS (Left panel) for flare sentinel optimized for a 60 mm×60 mm focal plane array (FPA) with 6 μm pixels, and all the optical elements of the IFS without the ray tracing (right panel). The image slicer as shown in the insert in the right panel follows the split slit design of MISI-36 has a total of 108 slicer mirrors. The width and length of the slits are 20μm, and 2.16 mm, respectively. The image slicer therefore has an imaging format of 54×108 pixels. The system therefore contains a total of 108 mini spectrographs arranged into a 6×18 array. There are a total of 432 optical elements, including 108 slicer mirrors, 108 off-axis parabolic mirrors with 75 mm focal length as the collimator mirrors, 104 micro gratings with 1200 line/mm groove density, 10 deg blaze operating in the 1st order, and 84 spherical camera mirrors with 75 mm focal length. Figure 3 shows the optical diagram of the IFS, plus pictures of the mechanical assembly and major components containing the active optical elements of a prototype that Canon recently fabricated successfully. Ray traces of five of the mini spectrographs are shown in the Zemax ray tracing (panel D). Panel C shows the compact spectrograph. Panel E is a view of the IFS exit port showing the dispersed spectra. The IFS covers the 3500–4500 Å spectral window, encompassing the hydrogen Balmer continuum and the Balmer series up to the Hγ line with $R = 800$ spectral resolution, limited by the width of the 20 μm slits. The beams for 3500, 4000, and 4500 Å are shown in green, blue, and red, respectively. This IFS provides a $54 \times 108 \times 1600$ (n_x, n_y, n_λ) format hyperspectral data cube in one exposure. The entire spectrograph resides in a compact 70 mm $\times$ 70 mm $\times$ 100 mm volume as shown in Panel C. All components were fabricated on Invar substrates, making the system mechanically robust for space missions.

The centerpiece of this new IFS design is the small monolithic image slicer block with 84 slicer mirrors each 20 μm $\times$ 0.84 mm in size, arranged in a 42×2 configuration located at the center of the image (see circle in Panel G). A scanning electron microscope image of the image slicer block appears in panel H. ***The ability to fabricate 20 μm slicer mirrors represents a major technology breakthrough in the field of imaging spectroscopy.*** This capability allowed us to incorporate the 6×14 miniature spectrographs array into the small volume yielding an exceptionally compact IFS without compromising optical performance. Panels A and F show the camera mirror array and collimator mirror array, respectively. Each component contains 84 small powered mirrors fabricated on a monolithic substrate. Since the gratings of all the mini spectrographs are identical, The grating array (panel B) consists of 6 surface-relieved gratings, also fabricated on a monolithic substrate. Each grating contains the 18 micro gratings for the 18 mini spectrographs in the collumn. The micro grating has a groove density of 1200 line/mm and a blazing angle of 14 deg. The spectrograph operates in the 1st order in the 350 − 450 nm wavelength window with grating $\alpha = 14.24$ degrees (400 nm) and spectrograph angle $\phi = 10$ degrees. The linear dispersion of the spectrograph is 0.09 mm/nm at 400 nm, and the 6 μm CMOS sensor pixels sample a 66 pm ($\lambda/\triangle\lambda = 6,100$) spectral window of the spectra at 400 nm. The illuminated width of the grating is approximately 3.0 mm, which yield a maximum theoretical spectral resolution of $\lambda/\triangle\lambda = 3,600$. However, the final spectral resolution of the miniature spectrograph is R = 1,900, limited by the 20 μm slit width. The successful fabrication of this challenging prototype demonstrates the feasibility of this new IFS design.

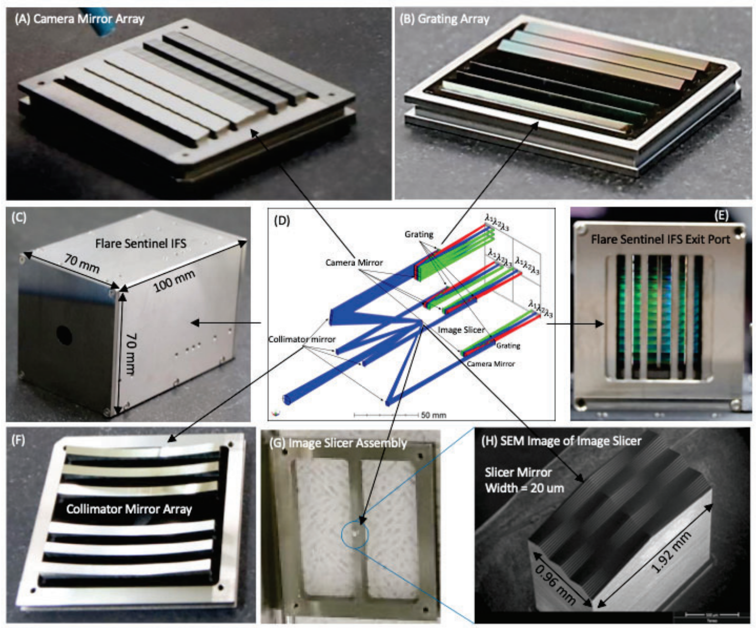

Figure 3. Optical design (Panel D) and pictures of a new compact IFS prototype assembly and its major optical components demonstrating the manufacturability of the new IFS design.

2.3 Conceptual Designs of Flare Sentinel

Figure 4 (left panel) shows the optical system of Flare Sentinel consists of a F/10.6 125 mm aperture Cassegrain telescope, and telecentric 2-lens 1:3 relay system, and a single integral field spectrograph as described in Section 2.2. The IFS thus sample the sun with a 1"/pixel spatial sampling size with a 54" × 108" FOV, sufficient to cover a substantial portion of a sunspot active regions. This large simultaneous field of view coverage will greatly increase the probability of Flare Sentinel to capture the entire evolutionary history of flares.

Given a FPA with certain physical size and pixel format, the instantaneous spatial and spectral sampling size and the hyperspectral FOV of the IFS based on the MICS design can be adjusted depending on the requirements of the measurements. For example, larger size gratings can be used to achieve higher spectral resolution. However, this will reduce the number of spectrographs that can be accommodated on the sensor and the instantaneous spatial field of view coverage of the IFS. Nevertheless, the compact size of MICS makes it possible incorporate multiple MICSs on a single telescope. The right panel of Figure 4 shows the layout of a Flare Sentinel consists of a Cassegrain telescope and four MICSs with four cameras. Therefore, the field of view coverage of the instrument can easily be doubled or quadrupled. Alternatively, the telescope can be reconfigured to reduce the spatial sampling size to 0.5"/pixel to improve the spatial resolution while maintaining the spatial FOV of the instrument. Yet another option is to reduce the number of mini spectrograph in each MICS to allow for more spectral pixel n_{lambda} per spectra to either increase the spectral sampling size and resolution of the instrument while maintaining the spectral window coverage, or to increase the spectral window coverage while maintaining the spectral sampling size and resolution. Figure 5 shows the CAD rendering of a Flare Sentinel with 4xMICS.

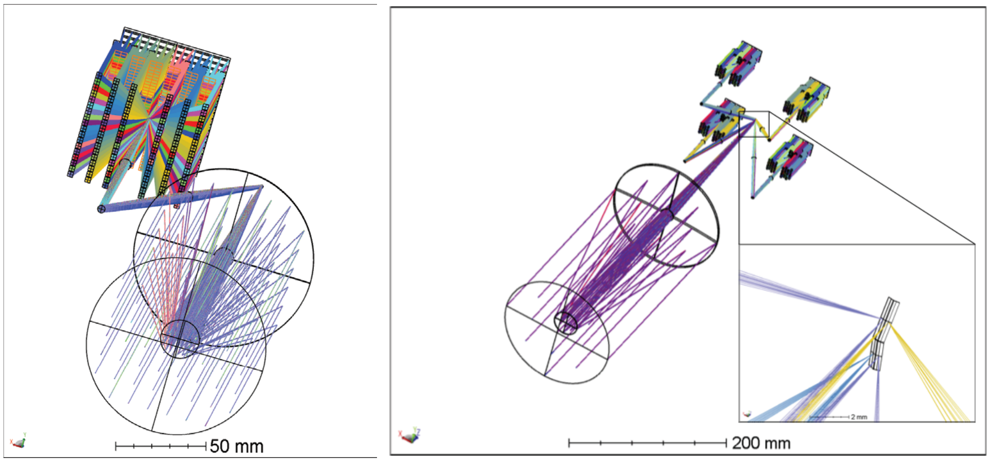

Figure 4. Left: Optical design of a Flare Sentinel incorporating a single IFS and a single FPA. Right: Example optical design of a Flare Sentinel instrument incorporating 4 IFSs recorded by 4 FPAs. A 2x2 field divider shown in the lower right-hand-corner divides the telescope focal plane into four subfields.

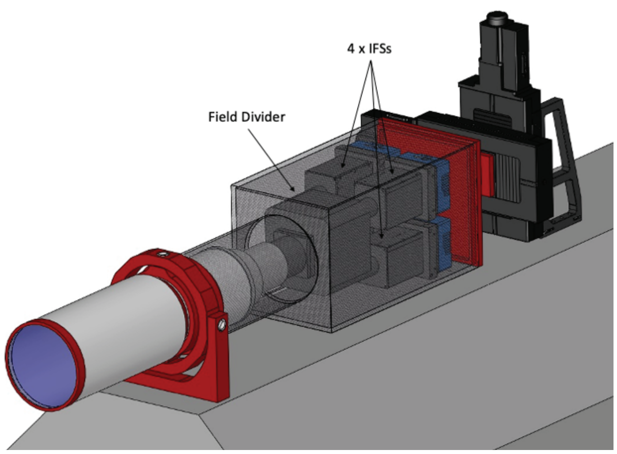

Figure 5. CAD rendering of a Flare Sentinel conceptual design incorporating 4xMICS.

3. SUMMARY

This paper describes the design of a machined image slicer compact spectrograph for integral field spectroscopy and two conceptual designs of Flare Sentinel, one incorporating a single MICS, and another with 4 MICS IFSs to illustrate the flexibility and scalability of this innovative new instrument design for the study of solar flares, or another phenomena that require high temporal resolution 2D spectroscopic measurements. A prototype MICS has been successfully fabricated. Performance evaluation will be commenced in the coming months.

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