Solar spectrum measured by waveguide spectral lens

Zhenming Ding ¹, Zhangqi Dang ¹, Xinhong Jiang ¹, and Ziyang Zhang ²

¹Affiliation not available
²Westlake University

October 31, 2023

Abstract

We demonstrate solar spectrum measurement in the visible-near-infrared region by integrated waveguide spectral lens (WSL). Light through the chip is dispersed and focused on a camera placed at the designed distance without any free-space lens. Commercial polymer materials with low propagation loss near visible region are chosen for wafer-scale fabrication. The solar radiation is coupled to a fiber via a home-made setup and the captured light is transmitted over ~50 m to the lab, where the spectrum is examined by two WSL chips for broadband and fine analysis, respectively. The observed O₂ (687.7 nm, 761.9 nm) and H₂O (718.4 nm) absorption lines are in good agreement with the results from a commercial optical spectral analyzer and the literature. This experiment proves the feasibility of using planar WSL chips as low-cost and versatile components for the development of compact and portable spectrometer equipment.
Solar spectrum measured by waveguide spectral lens

Zhenming Ding, Zhangqi Dang, Xinhong Jiang, and Ziyang Zhang

Abstract—We demonstrate solar spectrum measurement in the visible-near-infrared region by integrated waveguide spectral lens (WSL). Light through the chip is dispersed and focused on a camera placed at the designed distance without any free-space lens. Commercial polymer materials with low propagation loss near visible region are chosen for wafer-scale fabrication. The solar radiation is coupled to a fiber via a home-made setup and the captured light is transmitted over ~50 m to the lab, where the spectrum is examined by two WSL chips for broadband and fine analysis, respectively. The observed O$_2$ (687.7 nm, 761.9 nm) and H$_2$O (718.4 nm) absorption lines are in good agreement with the results from a commercial optical spectral analyzer and the literature. This experiment proves the feasibility of using planar WSL chips as low-cost and versatile components for the development of compact and portable spectrometer equipment.

Index Terms—Spectroscopy, integrated optics, planar lens.

I. INTRODUCTION

An optical spectrometer is a fundamental tool that splits light according to its spectral components, through which many physical or chemical phenomenon can be investigated. Integrated spectrometers are desired in many applications thanks to their compact size, light weight and flexible features [1, 2]. As waveguide-based dispersive devices, arrayed waveguide gratings (AWGs) were originally used in the wavelength division multiplexing system for optical communication [3, 4]. Over the years, such AWG devices have also found important applications in astronomy observation [5-7], chemical and medical sensing [8, 9].

In an AWG, the dispersed light is already focused within the chip on the curved surface tangential to the second slab facet. To obtain continuous spectra, e.g., for astronomy observation, the output waveguides must be cut away, and a free-space lens is needed to refocus light over a distance onto the camera [5-7]. In addition, the cut is usually done by wafer dicing along a straight line, but the internal focal plane is essentially curved. Therefore, aberration correction optics should be implemented to improve the image quality [7]. These free-space elements inevitably enlarge and complicate the spectrometer system. To solve this problem, the focusing function can be well integrated within the chip by adding additional waveguide length differences to the array according to the phase modulation of a convex lens. This type of devices are called waveguide spectral lens (WSL), which have been demonstrated in our previous work at near infrared region (NIR, around 1550 nm) [10, 11]. The dispersed light can then be directly focused on the camera without any free-space lens. Owing to the large focal depth, only millimeter alignment accuracy is required between the chip and the camera. The fiber-chip assembly can be conveniently packaged in a tube mountable to a camera [11].

For spectroscopic analysis, the visible-near-infrared region (VNIR) below 1.1 μm is of particular interest due to the specific characteristics of materials at these wavelengths and the availability of low-cost light sources and silicon-based detectors [12-15]. Although on-sky observations using AWGs have been demonstrated in NIR above 1.1 μm [5-7], there are no reported observation efforts so far, to the best of our knowledge, using integrated spectrometers in VNIR, where the absorption lines from the terrestrial solar spectrum provide important information of the chemical compositions in the Earth’s atmosphere such as O$_2$ and H$_2$O. This information is crucial for atmospheric physics and climatology. The absorption lines of O$_2$ and H$_2$O in planetary spectra are also key indicators to find habitable exoplanets [16]. The terrestrial solar spectra have been measured by free-space-based spectrometers using grooved gratings and focusing optics [17, 18]. However, these spectrometers have relatively large footprints and the system integration remain complex and at high cost.

In this work, we apply WSL chips to measure the solar spectrum in VNIR. Special materials and waveguide design are chosen for low-loss and single-mode operation. Compared to the existing WSL designs [10, 11], the free-space diffraction loss is further reduced by improving the output waveguide, allowing a narrow far-field envelope to suppress the unwanted diffraction orders. A simple, home-made setup is built to collect sunlight and couple it first into an optical fiber, through which light transmits flexibly over a long distance to the lab. The fiber-chip coupling adopts a standard procedure for integrated optics. The absorption lines of O$_2$ (A and B bands) and H$_2$O are observed in the broadband analysis and the two-dip details of O$_2$ (A band) can be resolved in the fine analysis. This work may serve as proof of concept for the development of advanced chip-based instrument for professional observations in atmospheric physics, climatology, and exoplanet exploration.
II. PRINCIPLE AND DEVICE DESIGN

Fig. 1 shows the schematic of the solar spectrum measurement system. An optical filter is added to avoid overlapping of the spectral lines in different diffraction orders beyond the free spectral range (FSR) of the chip. The chip itself consists of an input waveguide, a horizontal beam broadening area (BBA), and a waveguide array. The lengths of the waveguides in the array are designed to modulate the phase of light for both wavelength dispersion and beam focusing. The dispersion function is realized by introducing a fixed length difference between adjacent waveguides. Additional length differences are added according to the phase modulation of a convex lens for the focusing function. The output light of the chip with modulated wavefront creates a dispersed and focused image on a camera placed at the designed focal plane. Finally, the image is analyzed to extract the absorption lines of the sunlight, as plotted in insets (ii) and (iii) of Fig. 1.

In the measurement system, the working wavelength window of the WSL can be flexibly chosen for the target observation. The collection and spectral analysis of the solar irradiation can be carried out on different sites thanks to the low propagation loss and the variable length of the optical fiber. The packaged WSL module mounted to a commercial camera can also be applied to allow on-site detection [11].

Commercial polymer materials (WIR30-R1 series, ChemOptics) with low propagation loss at 830 nm are adopted in this work. The refractive indexes of the core and cladding materials are 1.466 and 1.45, respectively. The cross section of the waveguide core is 2.5 μm × 2.5 μm, as shown in inset (i) of Fig. 1. The size of the waveguide core and the materials are chosen so that a simple fabrication process involving only standard photolithography (SUSS MA6) is sufficient. The estimated coupling loss with the single-mode fiber (Nufern, S630-HP) is below 1 dB and the matched effective index also gives negligible back reflection.

The designed waveguide has a single-mode cutoff at 795 nm and the shortest wavelength to be detected is around 600 nm, at which the first-order mode (odd symmetrical mode) appears. However, the fiber remains single mode (symmetric, Gaussian-like) at 600 nm. For symmetric and center-alignment coupling from the fiber, the first-order mode in the waveguide cannot be generated efficiently. Similarly, at the output facet of the BBA, the first-order modes in the waveguides have low coupling efficiency with the output light field of the BBA.

Therefore, the waveguide behaves in the single-mode domain for the wavelength range in this study.

![Fig. 1. Schematic of the solar spectrum measurement system with a WSL chip. Inset (i) shows the design of the waveguide. Insets (ii) and (iii) plot the captured spectral lines and the corrected solar spectrum of O_2 (A band). BBA: beam-broadening area.](image)

![Fig. 2. (a) Schematic of the WSL for small FSR and fine spectral resolution (small FWHM). The inset shows the waveguides with output tapers designed for reducing the free-space diffraction loss. (b) Schematic of the WSL for large FSR and low spectral resolution, achieved by an additional arc. BBA: beam-broadening area. d: width and pitch of the waveguides at the chip facet.](image)

Fig. 2 illustrates two designs of WSLs enabling flexible adjustment of the length difference between adjacent waveguides. In Fig. 2(a), each waveguide path in the array consists of an input taper segment (L1), a straight segment (L2), an arc segment (L3), another straight segment (L4), and an output taper segment (L5). The input and output tapers have the same lengths for all waveguides, thus the length differences between the waveguides are determined by the segments L2, L3, and L4 in section (i). The length differences are designed for the dispersion and focusing functions according to the FSR and focal length [11]. The number of waveguides (N) in the array is determined by the required spectral resolution, i.e., full width at half maximum (FWHM), which can be approximated by FWHM = FSR/(1.13N) [11].

The structure in Fig. 2(a) is suitable for realizing WSLs with large length differences, corresponding to small FSRs and fine resolutions. However, if it is used for WSLs with large FSRs, the small length differences will lead to narrow spacing and large crosstalk between adjacent waveguides. To solve this problem, additional concentric arcs in sections (ii) and (iii) are added in the waveguide array, as depicted in Fig. 2(b).

Section (i) in Fig. 2(b) is the same as that in Fig. 2(a). Sections (ii) and (iii) are two groups of concentric arcs with angles of θ2 and θ1, respectively. The difference of radii between adjacent arcs is ΔR for both sections (ii) and (iii). The length difference for the dispersion function in section (i) is completely counteracted by the length difference between adjacent arcs (ΔL1 = θ1ΔR) in section (iii) as they have opposite curvatures [19]. Therefore, the length difference for the dispersion function in Fig. 2(b) is solely determined by the small length difference (ΔL2 = θ2ΔR) in section (ii). The length difference for the focusing function in Fig. 2(b) is kept the same as that in Fig. 2(a).

Improved from our previous work [10, 11], the free-space diffraction loss caused by unwanted diffraction orders is reduced by the new output waveguide design. Similar to the classic multi-slit interference, the unwanted diffraction orders can be suppressed by decreasing the width of the far-field envelope and increasing the angular separation between the adjacent diffraction peaks (Δθ ≈ 2arcsin(λ/(2d))) [20]. Here, d is the waveguide pitch at the chip facet, as shown in the inset of...
Fig. 2(a). The far-field envelope is determined by the diffraction pattern of a single waveguide. Therefore, the width of the far-field envelope can be decreased by increasing the waveguide width at the chip facet. For this purpose, waveguide tapers are added at the output side of the waveguides, as illustrated in the inset of Fig. 2(a).

### TABLE 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>WSL1</th>
<th>WSL2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_0$ (nm)</td>
<td>781.3</td>
<td>911.2</td>
</tr>
<tr>
<td>FSR (nm)</td>
<td>70.6</td>
<td>452.4</td>
</tr>
<tr>
<td>$m$</td>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td>$\Delta L$ (µm)</td>
<td>5.89</td>
<td>1.25</td>
</tr>
<tr>
<td>$N$</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>$f$ (cm)</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>$d$ (µm)</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

From the design principles above, two WSLs with different FSRs and spectral resolutions are made for fine (WSL1) and broadband (WSL2) measurements, respectively. The diffraction order is calculated as $m = \lfloor \lambda_0/\text{FSR} \times n_{eff} / \lambda \rfloor$, where $n_{eff}$ and $n_g$ are the waveguide effective index and group index, respectively, and the square brackets means rounding to the nearest integer [21]. The length differences for the dispersion function are calculated by $\Delta L = m \lambda_0 / n_{eff}$ [3]. The focal lengths ($f$) of the WSLs are set to 3 cm for a moderate beam broadening in the vertical dimension, limited to the detector size/height. To reduce the free-space diffraction loss but also avoid high crosstalk, the width and the pitch of the output waveguides at the chip facet are set to $d = 10 \mu m$.

Fig. 3. Simulated far-field intensity distribution and envelope at the central wavelength of WSL1. $\theta$: deflection angle. $\Delta \theta$ is the angular separation between adjacent diffraction peaks.

Fig. 4. (a) Photo of the fabricated devices and a matchstick for size comparison. WSL1 and WSL2 are used for the broadband and fine analysis of the solar spectrum, respectively. (b) Loss measurement result of the polymer waveguides at 824.6 nm.

Standard cutback measurement is performed using straight waveguides with different lengths (0.5 cm, 1 cm, and 2.5 cm) to extract the propagation loss (slope) and the fiber coupling loss with the single-mode fiber (intercept). The loss measurement result of the waveguides at 824.6 nm is shown in Fig. 4(b). Low propagation loss (~0.88 dB/cm) and fiber coupling loss (~0.68 dB/facet) are achieved.

### IV. CALIBRATION OF WSL SPECTROMETERS

A WSL spectrometer consists of an input fiber, a WSL chip, and a camera. Before the solar spectrum measurement, wavelength and intensity calibrations of the spectrometers should be performed. Wavelength calibration employs light sources with known spectral lines to establish a calibration line/curve that maps the pixel positions on the camera to the wavelengths. Intensity calibration is used to recover the actual spectrum by removing the contribution of the intensity response of the spectrometer from the recorded spectrum. The intensity response of a WSL spectrometer is wavelength-dependent and mainly comes from three sources: 1) the intensity responses of the fiber and the camera, 2) waveguide loss, primarily the absorption losses of the polymer materials, and 3) the intensity modulation by the far-field envelope. By comparing the recorded spectrum $S(\lambda)$ to the actual spectrum $E(\lambda)$ of a calibration source, the intensity response of the spectrometer can be calculated as $R(\lambda) = E(\lambda)/S(\lambda)$. Then the recorded spectrum $S_i(\lambda)$ of an unknown source is corrected as $E_i(\lambda) = R(\lambda)S_i(\lambda)$ [22, 23].

The wavelength and intensity calibrations are carried out according to the FSRs and target spectral ranges of the WSL spectrometers. For convenience, the spectrometers using WSL1 and WSL2 are denoted as S1 and S2, respectively. The target spectral range from 680 to 780 nm of S2 covers the absorption lines O$_2$ (A and B bands) and H$_2$O in the solar spectrum. The absorption line O$_2$ (A band) near 760 nm is further resolved by S1 with a target spectral range from 750 nm to 770 nm.

The wavelength calibrations of the WSL spectrometers are carried out using laser diodes (LDs) at selected wavelengths. The schematic diagram of the experimental setup is shown in Fig. 5. The LD light is injected into a fiber using a commercial collimator. A power monitor is used to detect the output power of the fiber during the optical alignment. After that, the light is coupled into a WSL chip. The output light is focused on a CMOS camera (Hikrobot, MV-CA050-10GM) for subsequent processing in the computer.
The wavelength calibration of S2 is realized using three LDs at 636.1 nm, 802.4 nm, and 824.6 nm, respectively. The captured spectral lines and the normalized intensity distributions are shown in Fig. 6(a) and (b), respectively. The wavelength calibration result is calculated using the spectral lines in the FSR indicated by the double-arrow line in Fig. 6(b), which have higher intensities in the target spectral range. The linear fit of the measured results is shown in Fig. 6(c). The linear relation between the pixel position and wavelength can be explained as follows. The deflection angle of a spectral line can be written as $\theta = \arcsin(\Delta \phi/(kd))$, where $\Delta \phi = n_{eff} \Delta L - 2\pi m$ is the phase difference between adjacent waveguides [24], $m$ is the diffraction order, and $k$ is the wavenumber. The deflection angle of a spectral line in the main lobe is smaller than the angular separation $(\Delta \theta)$ between adjacent diffraction peaks, which is measured to be 4.6° at 824.6 nm. A small $\theta$ is approximately $\Delta \phi/(kd) = n_{eff} \Delta L/d - m\lambda/d$, which has a linear relationship with $\lambda$. As a result, the pixel position of the spectral line $f \times \tan(\theta) \approx f \times \theta$ changes also linearly with $\lambda$.

The FSR and FWHM can be obtained from the results in Fig. 6(b) and (c). The measured FSR and FWHM are 403.6 nm and 4.4 nm at 824.6 nm, respectively. These values are in good agreement with the FSR (409.6 nm) and FWHM (4.4 nm) calculated by FSR $= \lambda/m \times n_{eff}/n_g$ and the simulated far-field intensity distribution [25].

The wavelength calibration of S1 is realized using three LDs at 784.2 nm, 802.4 nm, and 824.6 nm, respectively. The captured spectral lines of the three lasers are shown in Fig. 7(a). The normalized intensity distribution and the wavelength calibration result are shown in Fig. 7(b) and (c), respectively. The measured FSR and FWHM are 75 nm and 0.88 nm at 824.6 nm, respectively. These values are close to the calculated values (FSR = 74.5 nm, FWHM = 0.8 nm).

After the wavelength calibrations, the intensity calibrations of the WSL spectrometers are performed using broadband light sources, i.e., LEDs with different peak wavelengths. Optical filters are used to select the wavelength window within the FSR of the WSL. Filter 1 ($\lambda_c = 760.7$ nm, $\Delta \lambda_{0.5 \, \text{dB}} = 24.6$ nm) and Filter 2 ($\lambda_c = 711.2$ nm, $\Delta \lambda_{0.5 \, \text{dB}} = 178.2$ nm) are used in the intensity calibration for S1 and S2, respectively. Here, $\lambda_c$ is the central wavelength and $\Delta \lambda_{0.5 \, \text{dB}}$ represents the 0.5-dB bandwidth of the filter.

The schematic diagram of the experimental setup for the intensity calibration is shown in Fig. 8. The output of the LED is collimated by a lens, filtered and coupled into a fiber. The optical spectrum is measured by the commercial, well-calibrated optical spectrum analyzer (OSA, Yokogawa, AQ6370C) and the WSL spectrometer, respectively. The response of the WSL spectrometer can be calculated according to the measured optical spectra.

Two LEDs (LED1 and LED2) with different peak wavelengths are used in the intensity calibration of S2. Fig. 9 shows the intensity calibration results of S2 using LED1. The captured spectral lines are shown in Fig. 9(a). Based on the wavelength calibration result in Fig. 6(c), the normalized intensities at different wavelengths are obtained, as shown in Fig. 9(b). The optical spectrum of LED1 measured by the OSA is plotted in Fig. 9(c). By subtracting the intensity spectrum in Fig. 9(b) with the optical spectrum in Fig. 9(c), the relative intensity response of S2 can be obtained, as shown in Fig. 9(d).

Fig. 6. Wavelength calibration of S2. (a) Captured spectral lines at three wavelengths. (b) Normalized intensity distributions of the spectral lines. (c) Wavelength calibration result.

Fig. 7. Wavelength calibration of S1. (a) Captured spectral lines at three wavelengths. (b) Normalized intensity distributions of the spectral lines. (c) Wavelength calibration result.

Fig. 8. Schematic diagram of the experimental setup for intensity calibration of a WSL spectrometer.
The response in Fig. 9(d) is not smooth at wavelengths shorter than 727 nm, which can be attributed to the insufficient optical power from LED1, the higher absorption loss of the polymer materials, and the intensity modulation by the far-field envelope at these wavelengths.

To solve this problem, LED2 is added as an additional calibration source. The captured spectral lines and normalized intensity spectrum are shown in Fig. 10(a) and (b), respectively. Fig. 10(c) plots the optical spectrum of LED2, which has an optical power higher than that of LED1 at the wavelengths smaller than 727 nm. The calculated response in Fig. 10(d) is smoother than that in Fig. 9(d) from 680 nm to 727 nm. The relative intensity responses in Fig. 9(d) and 10(d) will be used to correct the solar spectrum measured by S2.

The intensity calibration of S1 employs LED3 with a central wavelength near 760 nm. The captured spectral lines and normalized intensity spectrum are shown in Fig. 11(a) and (b), respectively. The optical spectrum of LED3 measured by the OSA is plotted in Fig. 11(c). The calculated response of S1 is shown in Fig. 11(d). A smooth response is obtained from 750 nm to 770 nm.

**V. SOLAR SPECTRUM MEASUREMENT**

After wavelength and intensity calibrations, broadband and fine measurement of the solar spectrum are performed using S2 and S1, respectively. Fig. 12 illustrates the schematic diagram of the experiment. Sunlight is collected, filtered, coupled into the fiber, and transmits to the lab. The fiber is connected to a 1 × 2 splitter. One output (Port 1) is used to monitor the light power. The other (Port 2) is coupled to the WSL chip for spectrum measurement. The reference solar spectrum is measured by manually connecting Port 2 to the OSA.

Fig. 13(a) shows the photo of outdoor setup for collecting the sunlight. The optical filter and the fiber collimator are mounted on an adjustable holder. A portable computer is used to communicate with the measurement in the lab computer. Fig. 13(b) shows the indoor lab setup. The broadband solar spectrum is first measured by S2 and the OSA. The spectral resolution of the OSA is set to 2 nm, which is finer than that of S2 (4.4 nm). Fig. 14(a) and (b) show the captured spectral lines and the normalized intensity spectrum of the sunlight measured by S2. In Fig. 14(b), the measured intensities drop rapidly below 700 nm due to the higher absorption losses of the polymer materials and the intensity modulation by the far-field envelope. The spectra at the wavelengths smaller and larger than 727 nm are corrected using the responses in Fig. 9(d) and Fig. 10(d), respectively. The corrected solar spectrum and the spectrum measured by the OSA are shown in Fig. 14(c). The zoom-in view of the observed absorption lines is shown in Fig. 14(d). The absorption lines $O_2$ (A and B bands) and $H_2O$ are labelled in the figure. The wavelengths of the absorption lines

![Fig. 9. Intensity calibration of S2 using LED1. (a) Captured spectral lines of LED1. (b) Normalized intensity spectrum of the main lobe in (a). (c) Spectrum of LED1 measured by the OSA. (d) Relative intensity response of S2.](image1)

![Fig. 10. Intensity calibration of S2 using LED2. (a) Captured spectral lines of LED2. (b) Normalized intensity spectrum of the main lobe in (a). (c) Spectrum of LED2 measured by the OSA. (d) Relative intensity response of S2.](image2)

![Fig. 11. Intensity calibration of S1 using LED3. (a) Captured spectral lines of LED3. (b) Normalized intensity spectrum of the main lobe in (a). (c) Spectrum of LED3 measured by the OSA. (d) Relative intensity response of S1.](image3)

![Fig. 12. Schematic diagram of the experimental setup for the solar spectrum measurement using a WSL spectrometer and an OSA.](image4)
are in good agreement with the spectrum measured by the OSA and the literature [26].

![Fig. 13. Photos of the experimental setups for (a) coupling the sunlight into fiber and (b) measuring its spectrum using the WSL chip and the camera.]

![Fig. 14. Solar spectra measured by S2 and the OSA. (a) Captured spectral lines of the sunlight. (b) Normalized intensity spectrum of the main lobe in (a). (c) Corrected solar spectrum compared with the spectrum measured by the OSA. (d) Zoom-in view of the three absorption lines.]

![Fig. 15. Solar spectra measured by S1 and the OSA. (a) Captured spectral lines of the sunlight. (b) Normalized intensity spectrum of the main lobe in (a). (c) Corrected solar spectrum compared with the spectrum measured by the OSA.]

The absorption line O2 (A band) is further resolved by S1. Fig. 15(a) and (b) show the captured spectral lines and the normalized intensity spectrum. The response in Fig. 11(d) is used to correct the intensity spectrum in Fig. 15(b). The corrected solar spectrum measured by S1 and the result from the OSA are plotted in Fig. 15(c). The spectral resolution of the OSA is set as 0.5 nm, which is also finer than that of S1 (0.88 nm). The two dips of O2 (A band) are well resolved.

VI. CONCLUSION

To conclude, we have successfully captured the solar spectrum in VNIR below 1.1 μm using WSL chips with different FSRs and spectral resolutions. To the best of our knowledge, it is the first on-sky observation in this spectral region using integrated spectrometers. The free-space diffraction loss caused by unwanted diffraction orders is reduced by output waveguide design. In the measurement system, optical filters and WSL chips can be flexibly combined according to the target spectral range. The collection and spectral analysis of the light are carried out on different sites by transmitting the captured light in the flexible, low-loss optical fiber. The wavelengths of the absorption lines O2 (A and B bands) and H2O in the solar spectrum are in good agreement with the result from the OSA and the literature. This work proves the potential of WSL-based spectrometers and may lead to important applications in atmospheric physics, climatology, and exoplanet exploration.

For future development, waveguide loss needs to be largely improved at shorter wavelengths below 700 nm. This can be achieved by developing target polymer materials or using other waveguide technology, e.g., silica on silicon. To reach higher throughput in the tradeoff to some system complexity, a cylindrical lens can be used to focus light vertically. To expand the spectral range measured by the WSL spectrometer with small FSR but at fine resolution, a cross disperser can be placed after the cylindrical lens. The resulting image on the camera becomes two-dimensional dispersed spots instead of spectral lines. The calibration sources used in the calibrations can be replaced by more powerful and spectrally well-defined lamps and optical frequency combs for more accurate referencing. To prepare for the observation of dark celestial bodies, adaptive optics and wavefront correction equipment should be implemented to effectively couple light into a single-mode fiber, while this problem can be relaxed for space observations.

REFERENCES


