

HYPERSPECTRAL IMAGING SYSTEM

TECHNICAL FIELD

[0001] The present disclosure generally relates to a hyperspectral imaging system.

BACKGROUND

[0002] A hyperspectral imaging system is a technology that captures and processes data across spectral bands, providing detailed information about the composition and properties of objects. Unlike traditional imaging systems that capture data in a few discrete bands, hyperspectral imaging records continuous spectra, enabling precise identification and analysis of materials based on their unique spectral signatures. This technology finds applications in diverse fields such as remote sensing, agriculture, medical diagnostics, and defense, offering benefits such as enhanced detection capabilities, non-destructive analysis, and detailed spatial and spectral information.

[0003] Current MWIR hyperspectral imaging devices, however, are bulky and heavy, particularly those having a large aperture, such as those suitable for spaceborne applications, taking a toll on the total satellite payload. The limited availability of high-performance MWIR optics (mainly mirror-based or silicon or germanium-based) also translates into complex optical systems, requiring multiple elements with precise alignment. The complexity of such systems translates into expensive devices, even for ground-based applications (exceeding the million dollars per unit in some cases) and a high risk of failure upon deployment.

[0004] Therefore, there exists a need to provide an improved hyperspectral imaging system.

SUMMARY

[0005] According to a first aspect of the present disclosure, a hyperspectral imaging system is provided. The system may include: a first optical assembly configured to receive light and disperse the light into multiple channels; a second optical assembly configured to receive the light dispersed by the first assembly, and image each of the multiple channels of the light onto a focal plane array of a detector, wherein at least one of the first optical assembly and the second optical assembly includes a flat optic.

[0006] According to a first aspect of the present disclosure, a hyperspectral imaging system is provided. The system may include: a first optical assembly including a first refractive lens

and a first flat optic and configured to receive light and disperse the light into multiple channels; a second optical assembly including a second flat optic and one or two further refractive lenses and configured to receive the light dispersed by the first optical assembly and image each of the multiple channels of the light onto a focal plane array of a detector as a spectral signature; and the detector configured to form a hyperspectral data cube from the spectral signatures.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] FIG. 1 is a block diagram showing a hyperspectral imaging system according to various embodiments of the present disclosure.

[0008] FIG. 2 is a block diagram showing the hyperspectral imaging system of FIG. 1 according to various embodiments of the present disclosure.

[0009] FIGS. 3 a) and b) are schematic diagrams showing an exemplary hyperspectral imaging system in across-track cross-section and in along-track cross-section, respectively, according to various embodiments of the present disclosure.

[0010] FIGS. 4 a) and b) are schematic diagrams showing the light in the hyperspectral imaging system in across-tracking cross-section and in along-track cross-section, respectively, according to various embodiments of the present disclosure.

[0011] FIG. 5 a) is a phase profile of an exemplary metaatom design of the first flat optic, FIGS. 5 b) to e) are graphs for phase, constant group delay dispersion, constant group delay, and transmission of the exemplary metaatom design, respectively, FIG. 5 f) is a schematic diagram of the exemplary metaatom design of the first flat optic, and FIGS. 5 g) to i) are Scanning Electron Microscopy (SEM) graphs of exemplary metaatoms of the exemplary metaatom design of the first flat optic, according to various embodiments of the present disclosure.

[0012] FIGS. 6 a) to c) show intensity profiles of the focal spots and efficiencies obtained from Fourier Optics calculations for the first flat optic and the first refractive lens with respect to three exemplary wavelengths 4.8 μm , 4.25 μm , 3.7 μm , respectively, according to various embodiments of the present disclosure.

[0013] FIGS. 7 a) and b) are schematic diagrams of an exemplary metaatom design of the second flat optic, FIG. 7 c) is a phase profile of the exemplary metaatom design of the second flat optic, FIG. 7 d) is a schematic diagram of the exemplary metaatom design of the second flat optic, and FIG. 7 e) is a graph of exemplary metaatom spatial distribution and radii of the exemplary metaatom design of the second flat optic, according to various embodiments of the present disclosure.

[00014] FIG. 8 shows the final spot diagrams at the detector array of the ray tracing calculations for combinations of three wavelengths (i.e. 4.8 μm , 4.25 μm , 3.7 μm) and three swath angles (i.e. -1 degree, 0 degree, 1 degree, according to various embodiments of the present disclosure.

[00015] FIGS. 9 a) and b) shows photographs of fabricated flat optics, according to various embodiments of the present disclosure.

[00016] FIG. 10 shows a photograph of a prototype of a hyperspectral imaging system with casing open, according to various embodiments of the present disclosure.

DETAILED DESCRIPTION

[00017] Embodiments described below in the context of a method are analogously valid for the respective element, device, apparatus, or system, and *vice versa*. Furthermore, it will be understood that the embodiments described below may be combined, for example, a part of one embodiment may be combined with a part of another embodiment, and a part of one implementation may be combined with a part of another implementation.

[00018] It should be understood that the singular terms "a", "an", and "the" include plural references unless context clearly indicates otherwise. Similarly, the word "or" is intended to include "and" unless the context clearly indicates otherwise.

[00019] It will be further understood that the terms "comprise" (and any form of comprise, such as "comprises" and "comprising"), "have" (and any form of have, such as "has" and "having"), "include" (and any form of include, such as "includes" and "including"), and "contain" (and any form of contain, such as "contains" and "containing") are open-ended linking verbs. As a result, a method or device that "comprises," "has," "includes" or "contains" one or more steps or elements possesses those one or more steps or elements, but is not limited to possessing only those one or more steps or elements. Likewise, a step of a method or an element of a device that "comprises," "has," "includes" or "contains" one or more features possesses those one or more features, but is not limited to possessing only those one or more features. Furthermore, a device or structure that is configured in a certain way is configured in at least that way, but may also be configured in ways that are not listed.

[00020] Approximating language, as used herein throughout the specification and claims, may be applied to modify any quantitative representation that could permissibly vary without resulting in a change in the basic function to which it is related. Accordingly, a value modified by a term or terms, such as "about," "substantially", is not limited to the precise value specified

but within tolerances that are acceptable for operation of the embodiment for an application for which it is intended. In some instances, the approximating language may correspond to the precision of an instrument for measuring the value.

[00021] According to various non-limiting embodiments, the proposed hyperspectral imaging system may be a compact optical system design for air- or spaceborne hyperspectral imaging in push-broom configuration, combining conventional refractive optics and flat optics components. An air- or spaceborne hyperspectral imaging system in push-broom configuration may capture line images of objects or scenes at an angle and with a field of view (FOV) adapted to the typical altitude of the carrier platform, e.g., an airplane or satellite. By moving the carrier platform across the object or scene and repeatedly capturing and stitching spectrally resolved line images, a hyperspectral image may be obtained. By introducing flat optics components, heavy and complex conventional refractive optics components may be avoided or at least substituted by smaller and simpler components, thus improving cost-effectiveness. This may be especially the case for mid-wave infrared (MWIR) hyperspectral imaging, where complex refractive optical components, such as customized IR optics, are significantly more expensive compared to optical components in the visible, near-infrared (NIR) or short-wave infrared (SWIR) spectral ranges.

[00022] Complex optical systems comprised of conventional refractive optics components are generally bulky and heavy, whereas a reduction of weight and increase of compactness of a system often directly translates into a better cost-efficiency. Certain applications or a particular spectral range of interest usually require customized, achromatic refractive focussing optics which are usually not only bulky and heavy, but also comparably costly to be manufactured. Flat optical components (e.g. flat optics) may be comprised of small building blocks, so called metaatoms, which may be fabricated on a variety of substrates using standard fabrication methods such as electron beam, nanoimprint, or photolithography. Flat optical components may be very thin in one dimension, thus improving compactness and reducing weight a lot. The dimension which is very thin may be the height, which is usually uniform for large flat optical components. In the other two lateral dimensions, metaatom geometry design may have high degrees of freedom that may be used to realize a wide range of functionalities. The proposed air- or spaceborne hyperspectral imaging system with at least one flat optic may advantageously have a reduction of weight and fabrication costs.

[00023] According to various non-limiting embodiments, the proposed air- or spaceborne hyperspectral imaging system may include at least one flat optical component (i.e. flat optic) having special dispersive behaviour, which complements a train of refractive optical

components, to capture and disperse a line image of an object or scene and project the spatial and spectral information on a detector array. While at least one flat optical component is necessary, any refractive optical components of the system may be substituted by a flat optical component. In various embodiments, a flat optics (e.g. the second flat optic) may be utilized to reshape and redirect the dispersed light beams so that a pair of refractive lenses (e.g. the second and third refractive lenses) may image the dispersed line image through the cold stop of the detector. The proposed air- or spaceborne hyperspectral imaging system may use the special dispersive behaviour of flat optical components to capture and disperse a line image of an object or a scene at the same time. This may enable a compact optical system configuration suitable for space applications. The proposed air- or spaceborne hyperspectral imaging system may operate in the mid-wave infrared (MWIR) (e.g. a wavelength range from 3.7 μm to 4.8 μm), where each detector row captures a spectral band, and a ground sample distance of less than 13 m when the system is scaled for operation at a low altitude (e.g. 250 km). The proposed air- or spaceborne hyperspectral imaging system may allow reconstructing images corresponding to different wavelengths (spectral bands) of interest, thus providing spatial information of different objects, chemical species, materials or processes, enabling their identification and remote monitoring through their unique spectral “fingerprints”. The MWIR regime may be particularly important for two reasons: 1) it corresponds to the atmospheric transparency window, and 2) it may sense and measure signatures and spectral fingerprints of Green House Gases (GHG) such as CO_2 and CH_4 . Besides its spaceborne applications, the proposed hyperspectral imaging system may be used in other economic areas, such as real time monitoring of industrial activity, urban building energy efficiency, carbon footprint of cities, maritime security, natural disaster response, and environmental clean-up for plastic and oil pollutants.

[00024] According to various non-limiting embodiments, the proposed air- or spaceborne hyperspectral imaging system may allow replacing traditional optical components by ultra-thin ones - having a thickness around or below the operational wavelength. This technology, usually referred to as metasurfaces or flat optics, may consist of nano- patterned surfaces engineered to control the fundamental properties of light at will (amplitude, polarization and/or phase) and with extreme resolution (sub-wavelength). This may allow realizing complex optical functionalities, such as lensing, beam shaping, chromatic engineering... and even combinations of those, with similar or even superior performance than traditional optical trains including multiple components, in systems with greater simplicity and with extreme reduction of the device size and weight. The proposed air- or spaceborne hyperspectral imaging system may

allow combining several functionalities in a single optical element (~5cm) and, ultimately, a much simpler design that saves space and weight in the payload. The proposed air- or spaceborne hyperspectral imaging system may use the chromatic dispersion of flat optics by allowing to combine the two main optical components of hyperspectral imaging systems (a lens and a grating) into a single element (i.e. the first flat optic). A second flat optical component may be used to focus each spectral band into the corresponding pixels of the detector.

[00025] According to various non-limiting embodiments, the proposed air- or spaceborne hyperspectral imaging system may be manufactured based on traditional CMOS-compatible materials, in particular Si, with flat optics taking advantage of the full potential of semiconductor manufacturing. This may have several implications, namely: 1) that producing them at large scales may be very cost effective, which significantly lowers their price with respect to traditional optics, particularly of large-aperture, high-grade optical components; 2) that one may produce devices with many components and very complex functionalities, e.g. complex lens arrays with different optical parameters, sizes and shapes, at once, without the need to manufacture each component separately and assembling later, further reducing the cost and offering more flexibility in design; and 3) that one may monolithically integrate flat optical component in complex stacks to realize even more complex functionalities, removing the need for manual assembly and with the alignment capabilities of semiconductor manufacturing.

[00026] The following examples pertain to various aspects of the present disclosure.

[00027] Example 1 is a hyperspectral imaging system including: a first optical assembly configured to receive light and disperse the light into multiple channels; a second optical assembly configured to receive the light dispersed by the first assembly, and image each of the multiple channels of the light onto a focal plane array of a detector, wherein at least one of the first optical assembly and the second optical assembly includes a flat optic.

[00028] In Example 2, the subject matter of Example 1 may optionally include that the flat optic includes metaatoms made of a material selected from a group of materials including silicon, zinc sulphide, zinc selenide, calcium fluoride, germanium, silicon carbide, chalcogenide glasses, silicon dioxide, titanium dioxide, zinc oxide, aluminum dioxide (Al_2O_3), gallium nitride, silicon nitride and gallium phosphide.

[00029] In Example 3, the subject matter of Example 2 may optionally include that the metaatoms are formed in 2.5-dimensional (2.5D) metastructures having stacked layers of solid, hollow or core-shell like cylinders, crosses, triangles, or bars.

[00030] In Example 4, the subject matter of Example 2 or Example 3 may optionally include that when the first optical assembly includes a first flat optic, the first flat optic includes metaatoms of solid, hollow and core-shell cylinders with varying inner and outer diameters.

[00031] In Example 5, the subject matter of any of Examples 2 to 4 may optionally include that when the second optical assembly includes a second flat optic, the second flat optic includes metaatoms of solid cylinders with varying outer radii.

[00032] In Example 6, the subject matter of Example 5 may optionally include that a pitch of the metaatoms of the second flat optic of the second optical assembly is designed so as to cover 2π phase.

[00033] In Example 7, the subject matter of Example 4 may optionally include that the first optical assembly includes a first refractive lens and the first flat optic.

[00034] In Example 8, the subject matter of Example 7 may optionally include that the first flat optic of the optical assembly is arranged between the first refractive lens of the first optical assembly and the second optical assembly, the first refractive lens of the first optical assembly is configured to receive and refract the light, and the first flat optic of the first optical assembly is configured to receive and transmit the refracted light from the first refractive lens of the first optical assembly to the second optical assembly.

[00035] In Example 9, the subject matter of Example 7 or Example 8 may optionally include that the first flat optic of the first optical assembly is in an angle with the first refractive lens of the first optical assembly.

[00036] In Example 10, the subject matter of Example 7 or Example 8 may optionally include that the first flat optic of the first optical assembly is disposed in parallel with the first refractive lens of the first optical assembly.

[00037] In Example 11, the subject matter of Example 5 may optionally include that the second optical assembly further includes one or two further refractive lenses.

[00038] In Example 12, the subject matter of Example 11 may optionally include that the second flat optic of the second optical assembly is disposed in parallel with the one or two further refractive lenses of the second optical assembly in a manner that an optical axis of the second flat optic of the second optical assembly is in parallel with optical axes of the one or two further refractive lenses of the second optical assembly.

[00039] In Example 13, the subject matter of Example 12 may optionally include that a direction of the optical axes of the second optical assembly is tunable with respect to an optical axis of the first optical assembly.

[00040] In Example 14, the subject matter of any of Examples 11 to 13 may optionally include that the one or two further refractive lenses of the second optical assembly includes a second refractive lens and a third refractive lens, the second refractive lens configured to collimate the light and the third refractive lens configured to focus the light collimated by the second refractive lens.

[00041] In Example 15, the subject matter of any of Examples 1 to 14 may optionally include a slit array arranged close to the second optical assembly.

[00042] In Example 16, the subject matter of any of Examples 1 to 15 may optionally include a mirror in a light path of the light and configured to fold the light.

[00043] In Example 17, the subject matter of Example 7 or Example 11 may optionally include that at least one of the first refractive lens of the first optical assembly and the one or two further refractive lenses of the second optical assembly has an anti-reflection coating.

[00044] Example 18 is a hyperspectral imaging system including: a first optical assembly including a first refractive lens and a first flat optic and configured to receive light and disperse the light into multiple channels; a second optical assembly including a second flat optic and one or two further refractive lenses and configured to receive the light dispersed by the first optical assembly and image each of the multiple channels of the light onto a focal plane array of a detector as a spectral signature; and the detector configured to form a hyperspectral data cube from the spectral signatures.

[00045] In Example 19, the subject matter of Example 18 may optionally include that at least one of the first flat optic of the first optical assembly and the second flat optic of the second optical assembly is made of metaatoms.

[00046] In Example 20, the subject matter of Example 18 or Example 19 may optionally include that the second flat optic of the second optical assembly includes metaatoms of solid cylinders with varying outer radii, and/or wherein the first flat optic of the first optical assembly includes metaatoms of solid, hollow and core-shell cylinders with varying inner and outer diameters.

[00047] FIG. 1 is a block diagram showing a hyperspectral imaging system 100 in an operational environment according to various embodiments of the present disclosure.

[00048] A hyperspectral imaging system may be used to capture spatially resolved spectral information of an object or a scene. The object or scene may be illuminated with a broadband source (e.g. the nature light), and the reflected, scattered, or emitted light (e.g. denoted as 1 in FIG. 1) may be first imaged and then dispersed by a spectrometer to obtain the spatially resolved intensity of the light at different wavelengths. The data may be then processed to

create an image, in which each pixel holds a spectrum of the scene at that location. Spectral information obtained from the hyperspectral imaging system may be used to identify spectral fingerprints of various materials. Therefore, the hyperspectral imaging system may be a valuable tool in many fields such as agriculture, sensing, geology, mineralogy, and environmental monitoring. Typically, the hyperspectral imaging system may use a push-broom or a snapshot approach to capture spatially resolved spectral data. In snapshot systems, spectral images may be captured at once and image resolution may be sacrificed for a simplified data acquisition. In push-broom systems, the scene may be scanned line by line, which allows imaging with a high spatial resolution and high number of spectral bands at the cost of potential image stitching errors. To obtain the entire scene, the lines need to be stitched together in a post-processing step. The airborne or spaceborne hyperspectral imaging may be conducted from e.g., drones, airplanes, or satellites to capture spatially resolved spectral information on the ground. Satellites for hyperspectral imaging may be placed in Low Earth Orbit (LEO), i.e., at altitudes between 400 km to 800 km, which allows to capture images of large areas.

[00049] According to various non-limiting embodiments, the hyperspectral imaging system (or multispectral imaging system) 100 may be conveyed in an aircraft or space vehicle. The hyperspectral imaging system 100 may be used to acquire hyperspectral image data of an object or a scene in a swath direction 105 (also referred as an across-track direction 105), perpendicular to a direction of motion 101 of a sensor platform of the aircraft or space vehicle and scan the object or the scene along an along-track direction 103, parallel to the direction of motion 101.

[00050] According to various non-limiting embodiments, light 1 (i.e. optical energy) that is reflected, transmitted or scattered by the object or the scene (not shown) may be captured by the hyperspectral imaging system 100. This light 1 may then pass through various optical elements of the hyperspectral imaging system 100 including a dispersing element (e.g. a prism or grating, or a combination of a flat optic and a refractive lens in various embodiments) and/or a refocusing element (e.g. a refractive lens, or a combination of one or more flat optics and a refractive lens in various embodiments). The dispersed light by the dispersing element into constituent wavelengths may be refocused (e.g. reshaped, redirected) by the refocusing element onto a focal plane array 10 (e.g. of a detector) to form captured images. The captured images may be then converted to hyperspectral images or a data cube 12, i.e. a three-dimensional dataset generated by combining spatial (e.g. X and Y dimensions of the captured images) and spectral information (e.g. wavelengths).

[00051] According to various non-limiting embodiments, the hyperspectral imaging system 100 may be configured to capture light (i.e. optical energy) that is reflected, transmitted or scattered by the object or the scene through a slit 14. The slit 14 may be rectangular in shape and include a short dimension along the along-track direction 103 and a long dimension along the across-track direction 105. The slit 14 may be oriented so that the direction of motion 101 is parallel to the along-track direction 105 and perpendicular to the across-track direction 103.

[00052] According to various non-limiting embodiments, the hyperspectral imaging system 100 may include a plurality of functional optical components (e.g. five optical components), i.e., components that modulate light, out of which at least one is a flat optics component. In some embodiments, a refractive lens combined with a flat optical component (i.e. flat optic) may simultaneously capture and disperse a line image of an object or a scene. The object or scene may be captured at an angle, and the hyperspectral imaging system 100 may have a FOV and a ground sample distance scaled to the typical altitude of the carrier platform (e.g. the sensor platform). Crosstalk may be reduced, and discrete spectral bands may be filtered out by adding a slit array (e.g. the slit 14) or, when allowing spectral mixing, subsequent data postprocessing steps may deconvolute the spectral signal. Additionally or alternatively, a second flat optics component (i.e. a second flat optic) may act as a field lens to redirect and reshape the spectrally resolved line image towards two further conventional refractive lenses. These lenses may image the spectrally resolved line on a detector array (i.e. a focal plane array of the detector), whereas the detector pixel columns contain the spectral information and pixel rows may contain the spatial information or vice versa. The center wavelength may be in the MWIR, and the bandwidth may cover a range of wavelengths, e.g., from 3.7 μ m to 4.8 μ m.

[00053] FIG. 2 is a block diagram showing the hyperspectral imaging system 100 according to various embodiments of the present disclosure.

[00054] According to various non-limiting embodiments, the hyperspectral imaging system 100 may include a first optical assembly 110 configured to receive light and disperse the light into multiple channels; and a second optical assembly 120 configured to receive the light dispersed by the first assembly 110, and image each of the multiple channels of the light onto a focal plane array of a detector. At least one of the first optical assembly 110 and the second optical assembly 120 may include a flat optic.

[00055] In some embodiments, the first optical assembly 110 may be configured to receive the light and disperse the light into multiple channels with respect to incident angles of the

light. In other words, one channel of the multiple channels may correspond to one incident angle of the constituent incident angles of the light.

[00056] In some embodiments, the first optical assembly 110 may be configured to receive the light and disperse the light into multiple channels with respect to constituent wavelengths of the light. In other words, one channel of the multiple channels may correspond to one wavelength of the constituent wavelengths of the light.

[00057] According to various non-limiting embodiments, the second optical assembly 120 may be configured to image each of the multiple channels of the light onto the focal plane array of the detector in a manner that one wavelength of the light (i.e. one channel of the multiple channels) is directed onto one row of pixels of the focal plane array and another wavelength of the light (i.e. another channel of the multiple channels) is directed onto another row of pixels.

[00058] According to various non-limiting embodiments, the flat optic may include metaatoms made of a material selected from a group of materials including silicon, zinc sulphide, zinc selenide, calcium fluoride, germanium, silicon carbide, chalcogenide glasses, silicon dioxide, titanium dioxide, zinc oxide, aluminum dioxide (Al_2O_3), gallium nitride, silicon nitride and gallium phosphide. The metaatoms may be formed in 2.5-dimensional (2.5D) metastructures having stacked layers of solid, hollow or core-shell like cylinders, crosses, triangles, or bars. When the first optical assembly 110 include a first flat optic, the first flat optic may include metaatoms of solid, hollow and core-shell cylinders with varying inner and outer diameters. Additionally or alternatively, when the second optical assembly 120 includes a second flat optic, the second flat optic may include metaatoms of solid cylinders with varying outer radii. A pitch of the metaatoms of the second flat optic of the second optical assembly may be designed so as to cover 2π phase.

[00059] According to various non-limiting embodiments, the first optical assembly 110 may include a first refractive lens and the first flat optic. In some embodiments, the first flat optic of the optical assembly 110 may be arranged between the first refractive lens of the first optical assembly and the second optical assembly 120. The first refractive lens of the first optical assembly 110 may be configured to receive and refract the light, and the first flat optic of the first optical assembly 110 may be configured to receive and transmit (e.g. disperse) the light refracted from the first refractive lens of the first optical assembly 110 to the second optical assembly 120. Collectively, the first refractive lens and the first flat optic of the first optical assembly 110 may disperse the light into multiple channels.

[00060] In other embodiment, the first refractive lens of the first optical assembly 110 may be arranged between the first flat optic of the first optical assembly 110 and the second optical assembly 120. The first flat optic of the first optical assembly 110 may be configured to receive and transmit (e.g. disperse) the light, and the first refractive lens of the first optical assembly 110 may be configured to receive and refract the light transmitted from the first flat optic of the first optical assembly 110 to the second optical assembly 120. Collectively, the first refractive lens and the first flat optic of the first optical assembly 110 may disperse the light into multiple channels.

[00061] In some embodiments, the first flat optic of the first optical assembly 110 may be in an angle with the first refractive lens of the first optical assembly 110 (e.g. in the along-track cross-section). In other words, the first flat optic of the first optical assembly 110 may form an angle (e.g. an acute angle) with the first refractive lens of the first optical assembly 110. In some embodiments, the first flat optic of the first optical assembly 110 may be disposed in parallel with the first refractive lens of the first optical assembly 110 (e.g. in the across-track cross-section). That is, an optical axis of the first flat optic of the first optical assembly 110 may align with an optical axis of the first refractive lens of the first optical assembly 110. In some embodiments, an angle formed by the first flat optic of the first optical assembly 110 and the first refractive lens of the first optical assembly 110 may be tunable in response to an incident angle of the light, for example, by employing a rotatable flat optic and/or a rotatable refractive lens.

[00062] According to various non-limiting embodiments, the first optical assembly 110 may not include the first flat optic, but include a prism or grating for dispersing the light; the second optical assembly 120 may include the second flat optic.

[00063] According to various non-limiting embodiments, the second optical assembly 120 may include the second flat optic and one or two further refractive lenses (e.g. objective lenses). In some embodiments, the one or two further refractive lenses of the second optical assembly 120 may include a second refractive lens and a third refractive lens, the second refractive lens configured to collimate the light and the third refractive lens configured to focus the light collimated by the second refractive lens. The second flat optic of the second optical assembly 120 may be disposed in parallel with the one or two further refractive lenses of the second optical assembly 120 in a manner that an optical axis of the second flat optic of the second optical assembly 120 is in parallel with optical axes of the one or two further refractive lenses of the second optical assembly 120. A direction of the optical axes of the second optical assembly

120 may be tunable with respect to the optical axis of the first flat optic and/or the optical axis of the first refractive lens of the first optical assembly 110.

[00064] It shall be appreciated that the second optical assembly 120 may include any number of refractive lenses that are configured to focus the light dispersed by the first optical assembly 110 onto the focal plane array of the detector, for example, one refractive lens, three refractive lens or more. The first refractive lens of the first optical assembly 110 and the refractive lenses of the second optical assembly 120 may include any type, for example, double convex, double concave, plano-convex, plano-concave, meniscus Lens, achromatic lens, the like, or any combination thereof.

[00065] According to various non-limiting embodiments, at least one of the first refractive lens of the first optical assembly 110 and the one or two further refractive lenses of the second optical assembly 120 may have an anti-reflection coating.

[00066] According to various non-limiting embodiments, the hyperspectral imaging system 100 may further include a slit array arranged close to the second optical assembly 120.

[00067] According to various non-limiting embodiments, the hyperspectral imaging system 100 may further include a mirror in a light path of the light and configured to fold the light.

[00068] FIGS. 3 a) and b) are schematic diagrams showing an exemplary hyperspectral imaging system in the across-track cross-section 300a and in the along-track cross-section 300b, respectively, according to various embodiments of the present disclosure. FIGS. 4 a) and b) are schematic diagrams showing the light in the hyperspectral imaging system in the across-track cross-section 300a and in the along-track cross-section 300b, respectively, according to various embodiments of the present disclosure. FIGS. 3 a), 3 b), 4 a) and 4 b) show frames of references having two orthogonal axes, where z axis represents the altitude, x axis represents the swath direction (i.e. the across-track direction) and y axis represents the along-track direction in which the hyperspectral imaging system 300a, 300b, moves. The hyperspectral imaging system 300a, 300b may include the same or similar features of the hyperspectral imaging system 100. Accordingly, features that are described in the context of the hyperspectral imaging system 100 may correspondingly be applicable to the same or similar features in the hyperspectral imaging system 300a, 300b and vice versa. Furthermore, additions and/or combinations and/or alternatives as described for a feature in the context of the hyperspectral imaging system 100 may correspondingly applicable to the same or similar feature in the hyperspectral imaging system 300a, 300b and vice versa.

[00069] According to various non-limiting embodiments, the hyperspectral imaging system 300a, 300b may operate in a push-broom configuration. The hyperspectral imaging system 300a, 300b may image a single line of the object or scene in the across-track cross-section 300a, and disperse the light of the same line in the along-track cross-section 300b.

[00070] According to various non-limiting embodiments, the hyperspectral imaging system 300a, 300b may include a first optical assembly including a first refractive lens RL1 and a first flat optic FO1 and configured to receive light and disperse the light into multiple channels; a second optical assembly including a second flat optic FO2 and one or two further refractive lenses RL2, RL3 and configured to receive the light dispersed by the first optical assembly and image each of the multiple channels of the light onto a focal plane array of a detector D as a spectral signature (e.g. captured images); and the detector D configured to form a hyperspectral data cube from the spectral signatures (e.g. captured images). At least one of the first flat optic of the first optical assembly and the second flat optic of the second optical assembly may be made of metaatoms. The second flat optic of the second optical assembly may include metaatoms of solid cylinders with varying outer radii, and/or the first flat optic of the first optical assembly may include metaatoms of solid, hollow and core-shell cylinders with varying inner and outer diameters. According to various non-limiting embodiments, the first and second flat optics may include singlet metalens (i.e. with metaatoms on one surface (the surface on which the light is incident) of the flat optic), doublet metalens (i.e. with metaatoms on both surfaces of the flat optic), and metasurface spectrometer.

[00071] In the across-track cross-section as shown in FIG. 3a), the hyperspectral imaging system 300a may have a FOV that captures light with incident angles between θ_1 to θ_N . The first optical assembly including the first refractive lens RL1 and the first flat optic FO1 may then disperse the light into multiple channels, each channel corresponding to a respective incident angle of the incident angles between θ_1 to θ_N . The second optical assembly including a second flat optic FO2 and one or two further refractive lenses RL2, RL3 may then reshape, redirect and image the multiple channels on the focal plane array of the detector D as the spectral signatures (e.g. captured images).

[00072] In the along-track cross-section as shown in FIG. 3b), the light may be collected at an angle α_0 and dispersed into wavelengths λ_1 to λ_N by the first optical assembly RL1 and FO1. The dispersed field may be reshaped, redirected, and then imaged to the focal plane array of the detector D. The surface normal of the first flat optic FO1 may be tilted compared to the optical axis of the first refractive lens RL1 by an angle α_1 and the surface normal of the second

flat optic FO2 may be tilted compared to the optical axis of the first optic FO1 by an angle α_2 . RL1 and FO1 may be designed to capture light from an angle α_0 of 11.55 degrees.

[00073] It shall be appreciated that one or more of the refractive lenses RL1, RL2 and RL3 may be substituted by flat optical components and / or the flat optics FO1 may be substituted by a conventional refractive component, e.g., a common field lens. It shall be also appreciated that the sequence of RL1 and FO1 may be changed, meaning, that the light is first incident on FO1 and then passes through RL1. Different embodiments of RL1 and FO1 may meet combinations of across-track FOV requirements and the along-track angle α_0 from which line images are captured.

[00074] According to various non-limiting embodiments, a slit array may be added close to the position of the second flat optic FO2, e.g., for spectral cleaning and crosstalk reduction. Mirrors may be introduced in the light path to fold the light beam without changing the functionality or need for redesign of optical components. This may allow to fit the hyperspectral imaging system 300a, 300b, into various geometrical boundary conditions. All embodiments may be scaled to operate at different altitudes, e.g., 250 km or 500 km. Combinations of a variety of material choices of refractive optics components or flat optical components may lead to different embodiments. For example, a particular embodiment of FO1 for operation in MWIR spectral range may consist of a silicon substrate with a structured surface, i.e., silicon metaatoms. Other refractive lens, substrate or metaatom materials in the NIR, SWIR or MWIR may be e.g., Zinc sulphide, Zinc Selenide, Calcium Fluoride, Germanium, Silicon carbide or chalcogenide glasses. Combinations of common material choices may potentially be used to design different embodiments of flat optics or refractive optics that give the desired optical functionality in the proposed hyperspectral imaging system. For operation in the visible spectral range, possible material choices may include e.g., silicon dioxide, Titanium dioxide, Zinc oxide, Al_2O_3 , Gallium nitride, Silicon nitride and Gallium phosphide. Different embodiments of flat optical components may be realized by a variety of 2.5D metaatom geometries, e.g., cylinders, crosses, triangles, bars; all of which may be solid, hollow or core-shell like.

[00075] Referring to FIGS. 4 a) and b), a ray tracing calculation of the hyperspectral imaging system 300a, 300b is shown. In the across-track cross-section as shown in FIG. 4a), the hyperspectral imaging system 300a may have no tilts between the surface normal of optical components (i.e. RL1, RL2, RL3, FO1 and FO2). The light may be captured by RL1 and FO1 from -1 to 1 degrees, resulting in a FOV of 2 degrees. An enlarged diagram of the second

optical assembly FO2, RL2, RL3 and the detector D is shown in the inlet 401 of FIG. 4 a). The images at the focal plane array of the detector D may have a size of 7.2 mm.

[00076] In the along-track cross-section as shown in FIG. 4b), the light may be captured at RL1 at an incident angle α_0 of 0.0 degrees. The optical axes of RL1 and FO1 may be parallel (e.g. in alignment with each other) and have an aperture of 50 mm. In other words, an angle α_1 between the surface normal of FO1 and the optical axis of RL1 may be 0.0 degrees. A scale bar 403 is shown in FIG. 4 b). The centre-to-centre distance d_1 of RL1 and FO1 may be 10 mm. The surface normal at FO2 may be tilted by an angle α_2 of 62.232 degrees from the optical axis of FO1. The centre-to-centre distance d_2 of FO1 and FO2 may be 193.04 mm, the centre-to-centre distance d_3 of FO2 and RL2 may be 29.456 mm, the centre-to-centre distance d_4 of RL2 and RL 3 may be 30 mm, and the centre-to-centre distance d_5 of RL3 and the focal plane array of the detector D may be 28.644 mm. The hyperspectral imaging system 300a, 300b shall be not limited to have centre-to-centre distances as provided above and include any feasible configuration of the optical components of the hyperspectral imaging system 300a, 300b. The focal distances of RL2 (e.g. for collimating) and RL3 (e.g. for focussing) may be the same of 29.3 mm. The image at the focal plane array of the detector D may have a size of 10.4 mm. The cover glass of the detector D may be located 4.544 mm after RL3 and the cold stop aperture of the detector D may be located 3.63 mm after the cover glass and 20.47 mm before the focal plane array of the detector D. The distances d_1 to d_5 may be determined in relation to the cold stop aperture of the detector D so as to image on the detector D. For example, at an operation altitude of 250 km, the FOV of 2 degrees may translate to a swath width of 9 km with a ground sample distance of less than 13 m. The hyperspectral imaging system 300a, 300b may cover a wavelength range from 3.7 μm to 4.8 μm and the final, post-processed data may have a spectral resolution of less than 10 nm.

[00077] According to various non-limiting embodiments, the first refractive lens RL1 may be a silicon lens (e.g. a (positive) meniscus lens) with simple front and rear surface designs to keep fabrication costs low. The front surface of RL1 may be defined by the radius of curvature (ROC), e.g. of 248 mm, and a conic constant, e.g. of -0.37. The rear surface of RL1 may be defined by a radius of curvature, e.g. of 600 mm and having a spherical shape. The thickness of RL1 may range, e.g. from 2.8 mm to 8.5 mm and its diameter may be, e.g. 50 mm.

[00078] According to various non-limiting embodiments, the first flat optic FO1 may consist of silicon metaatoms on a silicon substrate (e.g. with a thickness of ~ 0.775 mm), or, in other words, it may consist of a ~ 0.775 mm thick silicon substrate with a structured surface. The desired phase and amplitude profile of the electric field may be mapped with the metaatoms

that locally fit the amplitude and phase requirements as obtained from optical simulations. In some embodiments, the metaatoms may be so designed to map the phase while providing a high transmitted field amplitude. In other embodiments, amplitude modulation or a combination of amplitude and phase modulation may be used to obtain the same functionality. The metaatoms mapping the amplitude and phase profile may have a variety of shapes (e.g. different combinations of height, pitch and metaatom geometries), for example, including a variety of cylindrical waveguide structures, such as solid, hollow, or core-shell cylinders with different inner and outer diameters. The height of the metaatoms may be $\sim 3.3 \mu\text{m}$ and the pitch between two metaatoms may be $\sim 1.45 \mu\text{m}$.

[00079] FIG. 5 a) is a phase profile of an exemplary metaatom design of the first flat optic FO1, FIGS. 5 b) to e) are graphs for phase, constant group delay dispersion, constant group delay, and transmission of the exemplary metaatom design, respectively, FIG. 5 f) is a schematic diagram of the exemplary metaatom design of the first flat optic FO1, and FIGS. 5 g) to i) are Scanning Electron Microscopy (SEM) graphs of exemplary metaatoms of the exemplary metaatom design of the first flat optic FO1. Exemplary metaatoms (e.g. eight different pillar structures) of the exemplary metaatom design is shown at the insets 501, 502 of FIGS. 5 b) and d), respectively. FIG. 5 a) shows that the exemplary metaatom design substantially covers a 2π phase. FIG. 5 b) shows that the design phase (dotted line) is mapped well by the phase delay caused by the metaatoms (solid line). The constant group delay and group delay dispersion, as shown in FIGS. 5 c) and d), respectively, may ensure the quality of the phase over the entire target spectral range. FIG. 5 e) shows a transmission of 60% or more (i.e. highly transmissive metaatoms), thereby a high efficiency of the exemplary metaatom design of FO1. The exemplary metaatoms may include a first hollow pillar, a solid pillar, a second hollow pillar, a third hollow pillar, a fourth hollow pillar, a fifth hollow pillar, a sixth core-shell pillar, a seventh hollow pillar, and an eighth core-shell pillar as seen from the left to right in the insets 501, 502. The pillars (e.g. cylinders) of the exemplary metaatoms may have varying inner radii and outer radii. The cores of the sixth core-shell pillar and the eighth core-shell pillar may have varying diameters. Each pillar structure of the exemplary metaatoms in the insets 501, 502 may correspond to a respective step in the phase graph of FIG. 5 b), for example, the solid pillar corresponds to phase of -1.5 rad. The FO1 may basically act as a broadband-efficient transmission grating. The metaatoms (e.g. the pillars, nanostructures) of the exemplary metaatom design of FO1 may be so designed (e.g. varying heights, radii, diameters, pitches, shapes, configurations) to map the required phase profile, achieve high transmission, and/or meet other requirements (e.g. the group delay may be constant as shown

in FIG. 5 d) with a close-to-zero group delay dispersion as shown in FIG. 5 c), insensitivity to polarization, etc). FIG. 5 f) shows the exemplary metaatom design of the first flat optic FO1 where an arrangement of different pillars (e.g. selected from the eight different pillar structures of the exemplary metaatoms as shown at the insets 501, 502 of FIGS. 5 b) and d)) is provided. [00080] To verify the focusing performance of RL1 and FO1, Fourier Optics calculations are used to obtain intensity profiles, for the minimum, centre, and maximum wavelength. The results of these calculations are presented in FIGS. 6 a) to c), showing expected focal spot shapes with focusing efficiencies larger than 60% for all the wavelengths including, 4.8 μm , 4.25 μm and 3.7 μm .

[00081] FIGS. 7 a) and b) are schematic diagrams of an exemplary metaatom design of the second flat optic FO2, FIG. 7 c) is a phase profile of the exemplary metaatom design of the second flat optic FO2, FIG. 7 d) is a schematic diagram of the exemplary metaatom design of the second flat optic FO2, and FIG. 7 e) is a graph of exemplary metaatom spatial distribution and radius (R, in micrometres) of the metaatom design of the second flat optic, according to various embodiments of the present disclosure. The exemplary metaatom design of the second flat optic FO2 may include a silicon substrate (e.g. with a thickness of ~ 0.775 mm) with a rectangular shape, and functional surface area 701 (e.g. 12 mm x 14 mm) and alignment markers 702 in three of the four corners, as shown in FIGS. 7 a) and b). FIG. 7 b) shows the origin (i.e. (x, y)=(0,0)) is in the centre of the second flat optic FO2. In contrast to FO1, the design of FO2 may be locally adapted for different wavelengths (e.g. as shown in FIG. 3 b)), as the light is already dispersed. The phase may be obtained as below:

$$\phi(x, y) = A_{x2} \left(\frac{x}{r_N} \right)^2 + A_{y2} \left(\frac{y - c_y}{r_N} \right)^2 + A_{y3} \left(\frac{y - c_y}{r_N} \right)^3 + A_{y4} \left(\frac{y - c_y}{r_N} \right)^4 + A_{y5} \left(\frac{y - c_y}{r_N} \right)^5$$

wherein ϕ is in radian and λ , x and y are in millimetres, the constants may be set as follows:

$$\begin{aligned} c_y &= 29.7 \text{ mm} \\ r_N &= 300 \text{ mm} \\ A_{x2} &= 6.1911593 \times 10^5 \\ A_{y2} &= 3.6540972 \times 10^6 \\ A_{y3} &= 3.3794398 \times 10^7 \\ A_{y4} &= 2.0431543 \times 10^8 \\ A_{y5} &= 3.5479504 \times 10^8 \end{aligned}$$

[00082] The wavelength may be obtained as below:

$$\lambda(y) = 11/104000 y + 17/4000$$

where λ is the wavelength and y is the y-coordinate in the along-track direction in millimetre. The metaatom design of the second flat optic FO2 may include metaatoms with a solid cylinder

with varying outer radii (e.g. in a range from about 0.4 μm to 1.15 μm). The pitch between metaatoms may be adapted to optimize full 2π phase coverage as well as high transmission (> 85%) for the dispersed wavelengths. The pitch may be obtained as below:

$$p(\lambda) = 0.2916323 \lambda + 0.0659949,$$

where p is the pitch and λ the wavelength in micrometre. The FO2 may act as a grating to redirect the light from the FO1 towards the detector D and be configured to be continuously adapted to the changing wavelength across it (e.g. a grating with continuously changing period). The metaatoms (e.g. the pillars, nanostructures) of the exemplary metaatom design may be so designed (e.g. varying heights, radii, diameters, pitches, shapes, configurations) to map the required phase profile and other requirements. FIG. 7 d) shows the exemplary metaatom design of the second flat optic FO2 where an arrangement of different solid pillars (e.g. with varying radii) is provided. For example, exemplary metaatoms may include a column of periodic four and/or five pillars with increasing/decreasing radii; stated differently, exemplary metaatoms may include a column of repeating four and/or five pillars with increasing/decreasing radii and adjacent columns may include different sequence of repeating four and/or five pillars with increasing/decreasing radii.

[00083] According to various non-limiting embodiments, both RL2 and RL3 may include aspherical convex-plano germanium lenses. The convex surfaces of RL2 and RL3 may be facing each other. The focal distance of both RL2 and RL3 may be 29.3 mm and the diameters of RL2 and RL3 may be 30 mm and 25.6 mm, respectively. The thickness of RL2 and RL3 may be 2.777 mm, and the radii of their curved surfaces may be 39.556mm. RL2 may be configured to collimate the diverging light from FO2. The collimated light may be then focused by RL3 on the focal plane array of the detector D. The choice of specifications of RL2 and RL3, e.g., their focal distances and sizes, may depend on the specifications of RL1, FO1 and FO2 as well as the specifications of the detector.

[00084] According to various non-limiting embodiments, MWIR detectors may need to be cooled to have a stable operating temperature. The aperture of the detector D, the so-called cold stop may be cooled down to and kept at a constant temperature to avoid unintended exposure of the detector array by MWIR light emission of parts of the system. This cold stop may limit the solid angles that may reach the focal plane array of the detector D and need to be considered for system design. The thickness of the cover slide (i.e. the cover glass), the cold-stop aperture, pixel sizes, and the overall detector array size and number of pixels may be important design parameters that, if varied, lead to different embodiments of the system. The detector D may include a Lynred Daphnis-HD MW detector, which has 16:9 HD format, featuring 1280 x 720

pixels with a pixel pitch of 10 μm . It may cover a spectral range from 3.7 μm to 4.8 μm . The detector D may need to be cooled down below 110 K, the cold stop diameter may be 5.118 mm, its thickness may be 0.3 mm, and the silicon cover slide may have a thickness of 1 mm.

[00085] According to various non-limiting embodiments, power throughput may be used to evaluate performance of the hyperspectral imaging system. Based on Fourier optics calculations and Fresnel reflection coefficients, an average focusing efficiency may increase from 14 % to 60%, if the hyperspectral imaging system contains one or more anti-reflection coated refractive lenses to reduce stray light.

[00086] According to various non-limiting embodiments, wavelength and spatial resolution may be also used to evaluate performance of the hyperspectral imaging system. Ideally, a single pixel may be used to record data of a single wavelength band and a single ground sample. FIG. 8 shows the final spot diagrams of FIGS. 6 a) to c) by the ray tracing calculations for combinations of three wavelengths and three swath angles. One square of the underlaid grid in FIG. 8 has a side length of 20 μm , so across the entire wavelength range and the entire FOV, the centre part of focal spots has a diameter which is only a factor of two to three larger than the detector pixel size, which is important for image resolution. Considering a particular detector pixel, at which light of a particular wavelength from a particular ground sample is collected, spectral crosstalk may refer to the effect that from another ground sample, light of a slightly different wavelength may reach the same detector pixel. This may be the case for all detector pixels, leading to a convoluted hyperspectral image. The ideal image may be reconstructed by deconvolution as the crosstalk is well defined.

[00087] FIGS. 9 a) and b) show photographs of fabricated flat optics, according to various embodiments of the present disclosure. FIG. 10 shows a photograph of a prototype of the hyperspectral imaging system with casing open, according to various embodiments of the present disclosure.

[00088] The prototype shown in FIG. 10 may only take 5U (cubesat units), even without applying any folding strategy. After measuring the resolution using the USAF target, even group 4 may be resolved in the across-track direction (containing the spatial information), corresponding to the quasi-diffraction limited spots predicted by simulations. TABLE 1 shows the performance characteristics of the demonstrator.

TABLE 1 The performance characteristics of the demonstrator

	1 st prototype
GSD	~10m@250km

Swath (FOV)	3.3 deg
Spectral Res.	<10nm (@MWIR)
Spectral Int.	~10nm (@MWIR)

[00089] While this specification contains many details, these should not be understood as limitations on the scope of what may be claimed, but rather as descriptions of features specific to particular examples. Certain features that are described in this specification or shown in the drawings in the context of separate implementations can also be combined. Conversely, various features that are described or shown in the context of a single implementation can also be implemented in multiple implementations separately or in any suitable sub-combination.

[00090] Similarly, while operations are depicted in the drawings in a particular order, this should not be understood as requiring that such operations be performed in the particular order shown or in sequential order, or that all illustrated operations be performed, to achieve desirable results. In certain circumstances, multitasking and parallel processing may be advantageous. Moreover, the separation of various system components in the implementations described above should not be understood as requiring such separation in all implementations, and it should be understood that the described program components and systems can generally be integrated together in a single product or packaged into multiple products.

[00091] A number of implementations have been described. Nevertheless, it will be understood that various modifications can be made. Accordingly, other implementations are within the scope of the following claims.

CLAIMS

1. A hyperspectral imaging system comprising:
a first optical assembly configured to receive light and disperse the light into multiple channels;
a second optical assembly configured to receive the light dispersed by the first assembly, and image each of the multiple channels of the light onto a focal plane array of a detector,
wherein at least one of the first optical assembly and the second optical assembly comprises a flat optic.
2. The hyperspectral imaging system of claim 1, wherein the flat optic comprises metaatoms made of a material selected from a group of materials including silicon, zinc sulphide, zinc selenide, calcium fluoride, germanium, silicon carbide, chalcogenide glasses, silicon dioxide, titanium dioxide, zinc oxide, aluminum dioxide (Al_2O_3), gallium nitride, silicon nitride and gallium phosphide.
3. The hyperspectral imaging system of claim 2, wherein the metaatoms are formed in 2.5-dimensional (2.5D) metastructures having stacked layers of solid, hollow or core-shell like cylinders, crosses, triangles, or bars.
4. The hyperspectral imaging system of claim 2 or claim 3, wherein when the first optical assembly comprises a first flat optic, the first flat optic comprises metaatoms of solid, hollow and core-shell cylinders with varying inner and outer diameters.
5. The hyperspectral imaging system of any of claims 2 to 4, wherein when the second optical assembly comprises a second flat optic, the second flat optic comprises metaatoms of solid cylinders with varying outer radii.
6. The hyperspectral imaging system of claim 5, wherein a pitch of the metaatoms of the second flat optic of the second optical assembly is designed so as to cover 2π phase.
7. The hyperspectral imaging system of claim 4, wherein the first optical assembly comprises a first refractive lens and the first flat optic.

8. The hyperspectral imaging system of claim 7, wherein the first flat optic of the optical assembly is arranged between the first refractive lens of the first optical assembly and the second optical assembly, the first refractive lens of the first optical assembly is configured to receive and refract the light, and the first flat optic of the first optical assembly is configured to receive and transmit the refracted light from the first refractive lens of the first optical assembly to the second optical assembly.

9. The hyperspectral imaging system of claim 7 or claim 8, wherein the first flat optic of the first optical assembly is in an angle with the first refractive lens of the first optical assembly.

10. The hyperspectral imaging system of claim 7 or claim 8, wherein the first flat optic of the first optical assembly is disposed in parallel with the first refractive lens of the first optical assembly.

11. The hyperspectral imaging system of claim 5, wherein the second optical assembly further comprises one or two further refractive lenses.

12. The hyperspectral imaging system of claim 11, wherein the second flat optic of the second optical assembly is disposed in parallel with the one or two further refractive lenses of the second optical assembly in a manner that an optical axis of the second flat optic of the second optical assembly is in parallel with optical axes of the one or two further refractive lenses of the second optical assembly.

13. The hyperspectral imaging system of claim 12, wherein a direction of the optical axes of the second optical assembly is tunable with respect to an optical axis of the first optical assembly.

14. The hyperspectral imaging system of any of claims 11 to 13, wherein the one or two further refractive lenses of the second optical assembly comprises a second refractive lens and a third refractive lens, the second refractive lens configured to collimate the light and the third refractive lens configured to focus the light collimated by the second refractive lens.

15. The hyperspectral imaging system of any of claims 1 to 14, further comprising:

a slit array arranged close to the second optical assembly.

16. The hyperspectral imaging system of any of claims 1 to 15, further comprising:
a mirror in a light path of the light and configured to fold the light.
17. The hyperspectral imaging system of claim 7 or claim 11, wherein at least one of the first refractive lens of the first optical assembly and the one or two further refractive lenses of the second optical assembly has an anti-reflection coating.
18. A hyperspectral imaging system comprising:
a first optical assembly comprising a first refractive lens and a first flat optic and configured to receive light and disperse the light into multiple channels;
a second optical assembly comprising a second flat optic and one or two further refractive lenses and configured to receive the light dispersed by the first optical assembly and image each of the multiple channels of the light onto a focal plane array of a detector as a spectral signature; and
the detector configured to form a hyperspectral data cube from the spectral signatures.
19. The hyperspectral imaging system of claim 18, wherein at least one of the first flat optic of the first optical assembly and the second flat optic of the second optical assembly is made of metaatoms.
20. The hyperspectral imaging system of claim 18 or claim 19, wherein the second flat optic of the second optical assembly comprises metaatoms of solid cylinders with varying outer radii, and/or wherein the first flat optic of the first optical assembly comprises metaatoms of solid, hollow and core-shell cylinders with varying inner and outer diameters.