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VARIABLE MICROFLUDIC OPTICAL FILTERS, HYPERSPECTRAL IMAGING SYSTEMS, AND METHODS OF HYPERSPECTRAL IMAGING INCORPORATING VARIABLE MICROFLUDIC OPTICAL FILTERS

Abstract

Provided herein are systems and methods of hyperspectral imaging microfluidic flow filters comprising flowable, optically-active bodies. These systems and methods provide novel light filtering systems and methods that improve spatial, spectral, and temporal resolution of hyperspectral imaging systems. In various aspects, the embodiments include measuring signals from a sensor array based on light reflected or emitted by the target, where a microfluidic channel system is arranged to allow light to pass through optically-active bodies flowing through the microfluidic channel system before reaching the sensor array.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application claims priority to U.S. Provisional Patent Application Ser. No. 63/553,219, filed on Feb. 14, 2024 and entitled “QUANTUM DOT FLOW FILTER”, the entirety of which is incorporated herein by reference.

FIELD OF THE DISCLOSURE

[0002] The present disclosure relates generally to flowable bodies containing optically-active components such as semiconductor nanocrystallites, i.e., “quantum dots” (QDs), and more specifically to hyperspectral imaging systems and methods of hyperspectral imaging that incorporate microfluidic optical filters comprising flowable optically-active bodies.

BACKGROUND

[0003] Colloidal quantum dots are semiconducting nanocrystals that generally have diameters below 20 nm, and as a result, exhibit quantum behavior due to the confinement of electrons within their structure. Physicists had recognized that size-dependent quantum effects could arise in nanoscale crystals since the mid twentieth century, but it was not until the 1980s and 1990s that the synthesis of these structures became suitable for practical applications. The discovery and development of quantum dots has enabled revolutionary advancements across various technologies including biomedical sensing, high-definition displays, photovoltaics, and imaging. In 2023, Moungi G. Bawendi, Louis E. Brus, and Aleksey Yekimov were awarded the Nobel Prize in Chemistry for their work related to quantum dots.

[0004] Still, many applications of quantum dots remain unexplored. In particular, the potential applications of quantum dots in the area of hyperspectral imaging has not yet been fully investigated or appreciated. Hyperspectral imaging systems aim to capture spatial, temporal, and spectral information from an imaging target (i.e., an object and/or scene). While conventional cameras use three visible light bands (red, green, and blue) to create images, hyperspectral imagers measure an imaging target across many bands (typically at least 10 bands) over a wide range of wavelengths (e.g., 250 nm to 15,000 nm). Because every material and compound reacts with light differently, the spectral signatures of imaged targets will also be different and therefore provide useful information. Hyperspectral imaging systems have applications in a number of areas, including environmental monitoring, machine vision, agriculture, medical imaging, minerology, defense, astrophysics, and many more. Nonetheless, hyperspectral imaging systems suffer from a number of drawbacks, including limited spatial resolution, limited spectral resolution, impractical physical designs, and/or complex computation requirements.

SUMMARY OF THE DISCLOSURE

[0005] According to one embodiment of the present disclosure, a hyperspectral imaging system is provided. The hyperspectral imaging system can include: a flow filter comprising a plurality of optically-active bodies and a microfluidic channel system, the microfluidic channel system defining a flow path for the plurality of optically-active bodies; and a sensor array comprising a plurality of light-sensitive elements, wherein each light-sensitive sensor is configured to measure light intensity based on light that is reflected and/or emitted by an imaging target located outside of the flow filter and modified by an optically-active body within the flow filter. In an aspect, the microfluidic channel system of the flow filter is arranged relative to the sensor array such that the light that is reflected and/or emitted by the imaging target passes through the microfluidic channel system before reaching one or more of the plurality of light-sensitive elements.

[0006] In an aspect, the plurality of optically-active bodies comprises at least three filter bodies having distinct absorbance and/or photoluminescence curves over a desired range of wavelengths.
[0007] In an aspect, the plurality of optically-active bodies comprises a repeating sequence of at least three filter bodies.
[0008] In an aspect, the plurality of optically-active bodies comprises at least fifty filter bodies having distinct absorbance curves over the desired spectrum.
[0009] In an aspect, the flow filter further can further include: a liquid continuous phase; and a continuous phase pump fluidly connected to the microfluidic channel system. In an aspect, the continuous phase pump is configured to pump the liquid continuous phase through the microfluidic channel system, and wherein the plurality of optically-active bodies are carried through the microfluidic channel system by the liquid continuous phase.
[0010] In an aspect, the plurality of optically-active bodies are ordered sequentially and carried sequentially through the microfluidic channel system.
[0011] In an aspect, each optically-active body of the plurality of optically-active bodies comprises a body medium and an optically-active component contained within the body medium.
[0012] In an aspect, the optically-active component comprises a plurality of quantum dots.
[0013] In an aspect, the plurality of optically-active bodies comprises at least three filter bodies having distinct absorbance and/or photoluminescence curves over a desired range of wavelengths, and the optically-active component of each of the at least three filter bodies comprises quantum dots having a different size and/or shape and/or composition.
[0014] In an aspect, the body medium comprises a liquid that is immiscible with the liquid continuous phase.
[0015] In an aspect, the body medium comprises at least one of a solid, a semi-solid, a gel, and a liquid polymer material.
[0016] In an aspect, the flow filter further comprises one or more optically opaque spacers disposed between each of the plurality of optically-active bodies.
[0017] In an aspect, the hyperspectral imaging system can further include a hyperspectral imaging controller. The hyperspectral imaging controller can include: one or more processors; and a non-transitory computer-readable memory storing instructions that, when executed by the one or more processors, causes the hyperspectral imaging controller to perform one or more of the following operations: (i) generating sensor data using the sensor array based on the light that is reflected and/or emitted by the imaging target, wherein the sensor data comprises, for each light-sensitive element of the sensor array, a plurality of light intensity measurements; and (ii) recovering a spectral signature for the imaging target based on the sensor data generated, wherein the spectral signature is recovered using a compressive sensing algorithm and/or a trained machine learning algorithm.
[0018] According to another embodiment of the present disclosure, a flow filter for moderating light is provided. The flow filter can include: a plurality of optically-active bodies, wherein each optically-active body comprises a body medium and an optically-active component contained within the body medium; a microfluidic channel system defining a flow path for the plurality of optically-active bodies; a liquid continuous phase configured to carry the plurality of optically-active bodies through the microfluidic channel system along the flow path; and a continuous phase pump fluidly connected to the microfluidic channel system, wherein the continuous phase pump is configured to pump the liquid continuous phase through the microfluidic channel system such that the liquid continuous phase carries the plurality of optically-active bodies through the microfluidic channel system along the flow path.
[0019] In an aspect, the plurality of optically-active bodies comprises at least three filter bodies having distinct absorbance and/or photoluminescence curves over a desired range of wavelengths, the optically-active component of the plurality of optically-active bodies comprises a plurality of quantum dots, and each of the at least three filter bodies comprise quantum dots having a different

size and/or shape and/or composition.

[0020] In an aspect, the body medium of the plurality of optically-active bodies comprises a liquid that is immiscible with the liquid continuous phase, and/or the body medium of the plurality of optically-active bodies comprises a solid, a semi-solid, a gel, and a liquid polymer material.

[0021] In an aspect, the plurality of optically-active bodies are ordered sequentially and carried sequentially through the microfluidic channel system.

[0022] According to still another embodiment of the present disclosure, a method of hyperspectral imaging is provided. The method may utilize a hyperspectral imaging system comprising a lens, a flow filter, a sensor array having a plurality of light-sensitive elements, and a hyperspectral imaging controller. The method can include: directing the lens of the hyperspectral imaging system towards an imaging target; flowing a plurality of optically-active bodies through a microfluidic channel system of the flow filter; receiving, through the lens of the hyperspectral imaging system, light that is reflected and/or emitted by the imaging target; measuring signals from one or more of the plurality of light-sensitive elements of the sensor array based on the light that is reflected and/or emitted by an imaging target located outside of the flow filter and modified by an optically-active body within the flow filter; and recovering, via one or more processors of the hyperspectral imaging controller, a spectral data for the imaging target based on the measured signals. In an aspect, the microfluidic channel system is arranged relative to the sensor array such that the received light that is reflected and/or emitted by the imaging target is passed through one or more of the plurality of optically-active bodies flowing within the microfluidic channel system before reaching one or more of the plurality of light-sensitive elements of the sensor array.

[0023] In an aspect, the plurality of optically-active bodies comprises at least three filter bodies having distinct absorbance and/or photoluminescence curves over a desired range of wavelengths, and the measured signals include light intensity measurements corresponding to the received light that has passed through each of the at least three filter bodies.

[0024] In an aspect, each optically-active body of the plurality of optically-active bodies comprises a body medium and an optically-active component contained within the body medium, the optically-active component comprises a plurality of quantum dots, and the plurality of optically-active bodies are ordered sequentially and flowed sequentially through the microfluidic channel system.

[0025] These and other aspects of the various embodiments will be apparent from and elucidated with reference to the embodiments described hereinafter.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0026] In the drawings, like reference characters generally refer to the same parts throughout the different views. Also, the drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the various embodiments.

[0027] FIG. **1** is a block diagram of a hyperspectral imaging system illustrated in accordance with aspects of the present disclosure.

[0028] FIG. **2** is a diagram of an imaging controller illustrated in accordance with aspects of the present disclosure.

[0029] FIG. **3** is a diagram of a flow filter illustrated in accordance with aspects of the present disclosure.

[0030] FIG. **4**A is a diagram of a flow filter arranged relative to a sensor array illustrated in accordance with aspects of the present disclosure.

[0031] FIG. **4**B is a diagram of a flow filter arranged relative to a sensor array illustrated in accordance with further aspects of the present disclosure.

[0032] FIG. **5**A is a diagram of an optically-active body illustrated in accordance with aspects of the present disclosure.
[0033] FIG. **5**B is a diagram of another optically-active body illustrated in accordance with aspects of the present disclosure.
[0034] FIG. **5**C is a diagram of still another optically-active body illustrated in accordance with aspects of the present disclosure.
[0035] FIG. **6** is a graph of absorbance curves for an optically-active component of different sizes over range of wavelengths illustrated in accordance with aspects of the present disclosure.
[0036] FIG. **7**A is a diagram of an exemplary sensor array illustrated in accordance with aspects of the present disclosure.
[0037] FIG. **7**B is a diagram of a plurality of optically-active bodies arranged relative to the sensor array illustrated in accordance with aspects of the present disclosure.
[0038] FIG. **8** is another diagram of a plurality of optically-active bodies arranged relative to the sensor array illustrated in accordance with aspects of the present disclosure.
[0039] FIG. **9** is a flowchart of a hyperspectral imaging method illustrated in accordance with aspects of the present disclosure.

DETAILED DESCRIPTION OF THE EMBODIMENTS

[0040] The present disclosure relates generally to flowable bodies containing optically-active components such as semiconductor nanocrystallites, i.e., “quantum dots” (QDs), and more specifically to hyperspectral imaging systems and methods of hyperspectral imaging that incorporate microfluidic optical filters comprising flowable optically-active bodies. As described herein, hyperspectral imaging systems measure optical spectra for many points across a target scene, often repeatedly, within a desired range of the electromagnetic spectrum. Hyperspectral imaging can provide detailed spectral information that allows for precise identification of materials and their properties, can be non-invasive and non-destructive, can detect subtle changes and variations in material, and can be used in a wide range of fields such as environmental monitoring, machine vision, agriculture, medical imaging, minerology, defense, astrophysics, and many more. As such, hyperspectral imaging can provide significant advantages over other types of sensing.
[0041] Two main hyperspectral imaging systems currently exist: spatial and spectral scanning imagers. Both, however, suffer from their own drawbacks. For example, a spatial scanner cannot quickly access all spectral information from an image at once and is limited by the scan speed. Further, scanners used in these imagers are often mechanical in nature and subject to breaking or misalignment.
[0042] On the other hand, a spectral scanning system may select a limited number of wavelengths of interest and project intensity data onto a detector, but spatial and/or temporal resolution may be sacrificed. Other forms of hyperspectral imaging have been developed, such as snapshot hyperspectral imaging where spectral data is instantaneously captured with spatial information.
[0043] However, these techniques are often costly and suffer from a sacrifice in spatial resolution or require complex computation. For example, current cutting-edge snapshot hyperspectral imaging technology generally uses either advanced mathematical techniques (e.g. compressive sensing) to extract a large data set from a limited sample or complex diffractive/filtering optics to sample a number of wavelengths.
[0044] Systems using mathematical techniques to resolve a signal require extensive computation and have yet to be demonstrated in a practical system fit for commercial or consumer use. Complex diffractive or filtering optics systems are expensive and often require mechanical movement and come at the expense of spatial resolution (e.g. the Cubert ULTRIS X20 can achieve 410×410 spatial pixels with 164 spectral bands). For comparison, a 1080p image is 1920×1080 pixels. Thus, there exists no cost effective or compact hyperspectral imaging system capable of high spatial (pixel-level) and high spectral (>50 bands) resolution while maintaining snapshot capability. In this respect, snapshot capability refers to the system's ability to capture hyperspectral images in a single

exposure, without the need for scanning, i.e., the entire scene is captured within seconds or less.

[0045] Accordingly, the present disclosure describes systems and methods that integrate hyperspectral imaging techniques with the use of microfluidic flows of optically-active bodies (e.g., quantum dots) to provide both high spatial, spectral, and temporal resolution. The systems and methods described herein may also address one or more other drawbacks of conventional hyperspectral imaging systems, which will be apparent based on this disclosure.

[0046] Turning now to FIG. **1**, a block diagram of an exemplary hyperspectral imaging system **100** is illustrated in accordance with certain aspects of the present disclosure. In embodiments, the hyperspectral imaging system **100** preferably includes a sensor array **102** and a flow filter **104**. As described herein, the hyperspectral imaging system **100** is configured to capture light from an imaging target **106**, which is then modulated (e.g., filtered) by one or more optically-active bodies that flow through the flow filter **104** before being measured at the sensor array **102**.

[0047] More specifically, when an imaging target **106** is illuminated by a light source **108**, the imaging subject will interact with the light from the light source **108** by absorbing, reflecting, and/or emitting electromagnetic radiation (e.g., light). Then, when the hyperspectral imaging system **100** is directed towards the illuminated imaging target **106**, the hyperspectral imaging system **100** can capture light that is reflected and/or emitted by the illuminated imaging target **106**. This captured light can be passed through the flow filter **104** to the sensor array **102**, which includes a plurality of light-sensitive elements configured to measure the intensity of the captured light after it has been modified by one or more optically-active bodies within the flow filter.

[0048] In embodiments, the hyperspectral imaging system **100** may include the light source **108** that at least partially provides the light exposure to the imaging target **106**. For example, the light source **108** can be, without limitation, a halogen lamp, an LED, a laser, an infrared lamp, an ultraviolet lamp, and/or the like, including combinations thereof. In some embodiments, the light source **108** can include multiple lamps of the same or different kind. In other embodiments, the hyperspectral imaging system **100** may not include its own light source **108**. For example, in some embodiments, the light source **108** may be the sun which illuminates the imaging target **106**.

[0049] In embodiments, the imaging target **106** can be an imaging target and/or scene. For example, in particular embodiments, the imaging target **106** may be crops in a field, minerals in an oil field, a biological tissue sample, and/or the like. However, it should be appreciated that anything capable of reflecting, absorbing, and/or emitting light may be imaged by the hyperspectral imaging system **100**. Furthermore, it should be appreciated that the imaging targets **106** contemplated herein are not the optically-active bodies that flow through the flow filter **104**. Rather, the imaging targets **106** are external to, i.e., outside of, the flow filter **104** as illustrated in FIG. **1**.

[0050] In embodiments, the sensor array **102** can include a plurality of light-sensitive elements, sometimes referred to a pixels. These light-sensitive elements or pixels can be arranged in a particular configuration, such as a linear or a two-dimensional array, depending on the specific technique utilized. Typically, the light-sensitive elements of the sensor array **102** are based either on a charged coupled device (CCD) or complementary metal-oxide-semiconductor (CMOS) technology. However, other types of light-sensitive technologies suitable for hyperspectral imaging may be utilized with the flow filters of the present disclosure.

[0051] In particular embodiments, the light-sensitive elements of the sensor array **102** may be configured to measure the intensity of light within a desired spectrum. For example, the light-sensitive elements may be configured to measure light intensity over one or more of the following spectral ranges:

TABLE-US-00001 Spectral Range Wavelength (nm) Visible (VIS) 400 to 700 Visible + Near Infrared (VNIR) 400 to 1,000 Near Infrared (NIR) 900 to 1,700 Short Wave Infrared (SWIR) 1,000 to 2,500 Mid Wave Infrared (MWIR) 3,000 to 5,000 Long Wave Infrared (LWIR) 8,000 to 14,000

[0052] In conventional imaging systems, the spectral resolution of the imaging system depends on the ability of the system to distinguish between different wavelengths, with higher spectral resolution indicating narrower spectral bands. According to the present disclosure, the hyperspectral imaging system **100** can have a spectral resolution that is dependent on the number of different optically-active bodies utilized in the flow filter **104**. In particular embodiments, the hyperspectral imaging system **100** can have a spectral resolution of less than a nanometer to tens of nanometers depending on the number of optically-active bodies used, their optical characteristics, and spectral recovery processes.

[0053] The spatial resolution of the hyperspectral imaging system **100** refers to the size of the smallest object that can be resolved in the captured image, which is typically determined by the size of the pixel. In particular embodiments, each light-sensitive element can have a pixel size of fractions of a micron to tens of microns, including a pixel size of about 5 μm.

[0054] The temporal resolution of a hyperspectral imaging system refers to the speed at which the sensor array **102** can capture all of the information necessary for spectral recovery and is typically measured in frames per second. Notably, this differs from the amount of times the sensor or individual pixels trigger per second since many intensity measurements must be taken per hyperspectral frame. In particular embodiments, the temporal resolution of the hyperspectral imaging system can vary from one to tens or hundreds of frames per second depending on the number of measurements needed per frame and the maximum trigger rate of the sensor/pixels.

[0055] Once the light that is emitted and/or reflected by the imaging target **106** is captured by the hyperspectral imaging system **100** and modified by an optically-active body in the flow filter **104**, this captured light (i.e., incident light) causes the light-sensitive elements of the sensor array **102** to generate signals based on the incident light's intensity. The hyperspectral imaging system **100** can then record and process these signals (i.e., sensor data) into a usable spectral data. In particular embodiments, the spectral data can be a hyperspectral data cube, where two dimensions represent the spatial information (x and y coordinates) and the third dimension represents the spectral information (wavelengths). However, it is contemplated that the sensor data generated by the sensor array **102** may be processed into other usable forms, as may be known in the art.

[0056] As also shown in FIG. **1**, the flow filter **104** can be arranged relative to the sensor array **102** such that the light that is reflected and/or emitted by the target **106** passes through at least a portion of the flow filter **104** before reaching the plurality of light-sensitive elements of the sensor array **102**. In particular, the flow filter **104** may be arranged relative to the sensor array **102** such that the light that is reflected and/or emitted by the target **106** passes through the one or more optically-active bodies flowed through a microfluidic channel system of the flow filter **104**.

[0057] In particular embodiments, the hyperspectral imaging system **100** can include an optical lens assembly **110** used to focus light from the imaging target **106** into the hyperspectral imaging system **100**. In further embodiments, the hyperspectral imaging system **100** may also include one or more other components and/or subsystems (not shown) as may be known in the art, including but not limited to, a scanning aperture and/or imaging optics such as various lenses, mirrors, and/or the like.

[0058] In embodiments, the hyperspectral imaging system **100** may include a hyperspectral imaging controller **112** operatively connected to the optical lens assembly **110**, the flow filter **104**, the sensor array **102**, and the other components (not shown) of the hyperspectral imaging system **100**. The hyperspectral imaging controller **112** can be configured to: (1) generate sensor data using the sensor array based on the light that is reflected and/or emitted by the imaging target **106**, wherein the sensor data comprises, for each light-sensitive element of the sensor array **102**, a plurality of light intensity measurements; and (2) recovering a spectral signature for the imaging target **106** based on the sensor data generated.

[0059] More specifically, with reference to FIG. **2**, a functional block diagram of an exemplary hyperspectral imaging controller **112** of a hyperspectral imaging system **100** is illustrated according to certain aspects of the present disclosure. As shown, the hyperspectral imaging controller **112** can include one or more processors **202** and a computer-readable memory **204** interconnected and/or in communication via a system bus **206** containing conductive circuit pathways through which instructions (e.g., machine-readable signals) may travel to effectuate communication, tasks, storage, and the like. The hyperspectral imaging controller **112** can be connected to a power source (not shown), which can include an internal power supply and/or an external power supply. In embodiments, the hyperspectral imaging controller **112** can also include one or more additional components, such as a user interface **208**, a display **210**, an input/output (I/O) interface **212**, a networking unit **214**, and the like, including combinations thereof. As shown, each of these components may be interconnected and/or in communication via the system bus **206**, for example.

[0060] In embodiments, the one or more processors **202** can include one or more high-speed data processors adequate to execute the program components described herein and/or perform one or more operations of the methods described herein. The one or more processors **202** may include a microprocessor, a multi-core processor, a multithreaded processor, an ultra-low voltage processor, an embedded processor, and/or the like, including combinations thereof. The one or more processors **202** can include multiple processor cores on a single die and/or may be a part of a system on a chip (SoC) in which the processor **202** and other components are formed into a single integrated circuit, or a single package. That is, the one or more processors **202** may be a single processor, multiple independent processors, or multiple processor cores on a single die.

[0061] In embodiments, the user interface **208** may be configured to receive various forms of input from a user associated with the imaging controller **112**. The user interface **208** can include, but is not limited to, one or more of a keyboard, keypad, trackpad, trackball(s), capacitive keyboard, controller (e.g., a gaming controller), computer mouse, computer stylus/pen, a voice input device, and/or the like, including combinations thereof.

[0062] In embodiments, the display device **210** may be configured to display information, including text, graphs, and/or the like. The display device **210** can include, but is not limited to, a liquid crystal display (LCD), a light-emitting diode (LED) display, a touch screen or other touch-enabled display, a foldable display, a projection display, and so on, or combinations thereof.

[0063] In embodiments, the input/output (I/O) interface **212** may be configured to connect and/or enable communication with one or more peripheral devices (not shown), including but not limited to additional machine-readable memory devices, diagnostic equipment, and other attachable devices. The I/O interface **212** may include one or more I/O ports that provide a physical connection to the one or more peripheral devices. In some embodiments, the I/O interface **212** may include one or more serial ports.

[0064] In embodiments, the networking unit **214** may include one or more types of networking interfaces that facilitate wired and/or wireless communication between the hyperspectral imaging system **100** and one or more external devices. That is, the networking unit **214** may operatively connect the hyperspectral imaging system **100** to one or more types of communications networks **216**, which can include a direction interconnection, the Internet, a local area network ("LAN"), a metropolitan area network ("MAN"), a wide area network ("WAN"), a wired or Ethernet connection, a wireless connection, a cellular network, and similar types of communications networks, including combinations thereof. In some embodiments, the hyperspectral imaging system **100** may communicate with one or more remote/cloud-based servers and/or cloud-based services, such as a remote server **218** for data storage, via the communications network **216**.

[0065] In embodiments, the memory **204** can be variously embodied in one or more forms of machine accessible and machine-readable memory. In some embodiments, the memory **204** includes a storage device (not shown), which can include, but is not limited to, a non-transitory storage medium, a magnetic disk storage, an optical disk storage, an array of storage devices, a solid-state memory device, and/or the like, as well as combinations thereof. The memory **204** may also include one or more other types of memory, such as dynamic random-access memory (DRAM), static random-access memory (SRAM), erasable programmable read-only memory (EPROM), electrically erasable programmable read-only memory (EEPROM), Flash memory, and/or the like, as well as combinations thereof. In embodiments, the memory **204** may include one or more types of transitory and/or non-transitory memory.

[0066] The imaging controller **112** can be configured by software components stored in the memory **204** to: (1) process the signals measured by the sensor array **102** to form, for example, a hyperspectral data cube; (2) store and retrieve large volumes of data generated by the hyperspectral imaging system **100**; and/or (3) manage the operation of the entire hyperspectral imaging system **100**. In particular embodiments, the memory **204** can be configured to store data/information **220** and computer-readable instructions **222** that, when executed by the one or more processors **202**, causes the imaging controller **112** to at least: (1) measuring and recording signals from the plurality of light-sensitive elements of the sensor array **102**; and (2) recovering spectral data based on the measured signals.

[0067] The imaging controller **112** may also include an operating system component **226**, which may be stored in the memory **204**. The operating system component **226** may be an executable program facilitating the operation of the hyperspectral imaging system **100**. Typically, the operating system component **226** can facilitate access of the I/O interface **212**, network interface **214**, the user interface **208**, and the display **210**, and can communicate or control other components of the hyperspectral imaging system **100**.

[0068] As described herein, the hyperspectral imaging system **100** includes a flow filter **104**, which can be a variable microfluidic optical filter that is configured to modulate the incident light captured by the hyperspectral imaging system **100** before it reaches the sensor array **102**. More specifically, in accordance with aspects of the present disclosure, the flow filter **104** is configured to flow a plurality of optically-active bodies through microfluidic channels as the incident light is captured, such that the optically-active bodies modulate the incident light before being measured by the sensor array **102**.

[0069] With reference to FIG. **3**, an exemplary flow filter **104** is illustrated according to certain aspects of the present disclosure. As shown, the flow filter **104** comprises a fluidic channel system **302**, a continuous phase pump **304**, and optionally a flow filter controller **306**. In embodiments, the flow filter controller **306** is embodied like the imaging controller **112** describe above, but is configured to operate the flow filter **104**, i.e., the continuous phase **304** to cause the flow of the optically-active bodies **308**. However, in some embodiments, the functionality of the flow filter controller **306** may be integrated into the imaging controller **112**. As described herein, the flow filter **104** can also include a plurality of optically-active bodies **308** and a continuous phase **310** that is adapted to carry the optically-active bodies **308** through the fluidic channel system **302**.

[0070] In embodiments, the fluidic channel system **302** may be a microfluidic channel system **302** that is arranged relative to the sensor array **102** such that incident light from the imaging subject **106** passes through the fluidic channel system **302** (and the contents of the channels) before reaching the sensor array **102**. For example, as shown in the examples of FIGS. **4**A and **4**B, the microfluidic channel system **302** is arranged relative to the sensor array **102** such that incident light L passes through the channel system **302** before reaching one or more light-sensitive elements **402** of the sensor array **102**. While the channel system **302** is shown as covering only a portion of the sensor array **102**, the channel system **302** preferably extends to cover the entire sensor array **102**.

[0071] As described herein, the microfluidic channel system **302** includes one or more fluidic channels **404** through which the optically-active filter bodies **308** may be flowed. It is contemplated that the channels **404** of the channel system **302** may take a number of different arrangements and configurations. For example, as shown in the example of FIG. **4**A, the channel system **302** may comprise a winding channel **404** that snakes in alternating directions across the sensor array **102**. In some embodiments, the channel system **302** may include an inlet **406** and an outlet **408** where the optically-active filter bodies **308** are introduced and removed. However, in other embodiments, the channel system **302** may be a closed circuit whereby the optically-active filter bodies **308** remain within the one or more channels **404**.

[0072] In specific embodiments, the microfluidic channel system **302** comprises one or more channels **404** having a channel size configured to sequentially flow individual optically-active bodies **308**. That is, the channel size of the one or more channels **404** can be based on the size of the optically-active bodies **308** such that incident light passes through only one optically-active body **308** before reaching a light-sensitive element **402** of the sensor array **102**. In specific embodiments, the channel system **302** may include one or more channels **404** having a channel diameter which corresponds to the size of a pixel, which may span from fractions of a micron to tens of microns (i.e., less than about 1 μm to less than about 100 μm).

[0073] As mentioned above, the flow filter **104** preferably includes a plurality of optically-active bodies **308** and a liquid continuous phase **310**. In embodiments, each of the optically-active bodies **308** are individually tuned to modulate the incident light captured by the hyperspectral imaging system **100** in a non-random manner. Further, the optically-active bodies **308** are configured to be flowable through the channel system **302** by the liquid continuous phase.

[0074] In embodiments, the optically-active bodies **308** comprise a body medium and an optically-active component that is contained within the body medium. For example, with reference to FIGS. **5**A-**5**C, several optically-active bodies **508**A, **508**B, **508**C are illustrated in accordance various aspects of the present disclosure. As shown, the optically-active bodies **508**A, **508**B, **508**C can have a different shapes and comprise a body medium **504** that contains an optically-active component **502**. In one embodiment, the optically-active bodies **508**A may have a spherical shape. In another embodiment, the optically-active bodies **508**B may have a slug shape. In yet another embodiment, the optically-active bodies **508**C may have a flattened or “pancaked” shape. Still, it is contemplated that other shapes are possible, e.g., cylindrical bodies, etc.

[0075] In embodiments, the size and shape of the optically-active bodies **308** may be defined relative to the size of the light-sensitive elements **404**, such that at single optically-active body **308** entirely covers one or more light-sensitive elements **404**. For example, in some embodiments, the light-sensitive elements **404** may have a square shape with a length/width of about 5 μm, and so each optically-active body **308** may have a length/width and/or diameter of about 5 μm to cover the entire light-sensitive elements **404**. In specific embodiments, the optically-active bodies **308** may have a volume on the order of picoliters (i.e., from about 1 pL to about 1000 pL).

[0076] In some embodiments, the body medium **504** of the plurality of optically-active bodies **508**A, **508**B, **508**C can comprise a liquid that is immiscible with the liquid continuous phase **310**. For example, the liquid continuous phase **310** might be polar (e.g. water), and the body medium **504** might be nonpolar (e.g. toluene), such that the two phases do not mix

[0077] In further embodiments, the body medium **504** of the plurality of optically-active bodies **508**A, **508**B, **508**C can comprise a solid, a semi-solid, a gel, and a liquid polymer material. For example, the polymer material might include a polydimethylsiloxane (PDMS) base and a crosslinker, e.g. Sylgard™ **184**.

[0078] In embodiments, the body medium **504** of the plurality of optically-active bodies **508**A, **508**B, **508**C is configured to contain and/or otherwise support the optically-active components **502** of the optically-active bodies **508**A, **508**B, **508**C. Thus, according to various embodiments, the optically-active bodies **508**A, **508**B, **508**C can be a mixture of the body medium **504** and the optically-active component **502**, including but not limited to, an emulsion, a suspension, a composite, and/or the like. In further embodiments, the optically-active bodies **508**A, **508**B, **508**C can also and/or alternatively encapsulate the optically-active component **502**. For example, the optically-active bodies **508**A, **508**B, **508**C can comprise a hard shell surrounding a fluid containing quantum dots.

[0079] According to the present disclosure, the optically-active bodies **508**A, **508**B, **508**C will have a non-random absorption and/or photoluminescence curve over a desired range of wavelengths that is dominated by the optical properties of the optically-active component **502**. In specific embodiments, the optically-active component **502** can include a plurality of quantum dots, such as non-emissive and/or emissive quantum dots. With reference to FIG. **6**, examples of absorbance curves of PbS quantum dots ranging in size from 2.2 nm to 11.5 nm (produced by Quantum Solutions® under the brand name QDot™) are illustrated. However, it should be appreciated that other optically-active components **502** (e.g., quantum dots of other compositions, etc.) will have different absorbance and emission curves.

[0080] The incident light L passing through an optically-active body **508** will be modified according to the non-random optical characteristics of the body, which are largely determined by the optically-active components **502**. A non-random optical characteristic may, for example, include an absorption edge within the range of wavelengths of interest. Accordingly, by flowing a plurality of optically-active bodies **508**, with varying optical characteristics (e.g. shifted absorbance edges), over a light-sensitive element **402**, light intensity measurements can be generated by the light sensitive element **402** and used for spectral recovery.

[0081] With reference to FIGS. **7**A and **7**B, a portion of a sensor array **102** and a microfluidic channel **704** are illustrated in accordance with certain aspects of the present disclosure. The microfluidic channel **704** aligned with a row of light-sensitive elements **402** and is configured to flow a plurality of filter bodies **708**A-G over these elements **402**. For simplicity, one element (or pixel) **702** is highlighted, and a series different optically-active bodies **708**A-G are shown flowing over the pixel of interest **702**. Because each of the optically-active bodies **708**A-G have different absorbance features at different wavelength bands (e.g., based on the distinct absorption curves of the different optically-active components **502**), the light intensity observed by the pixel of interest **702** will vary is a non-random manner. The signal (i.e., sensor data) generated by the pixel of interest **702** can then be used to recover a spectral information within a desired range of wavelengths for the incident light L.

[0082] As shown in FIG. **7**B, the plurality of filter bodies **308** can include at least seven distinct filter bodies **708**A-G with sufficiently distinct absorbance features. However, for some applications, fewer or additional distinct filter bodies **708**A-G may be used. For example, in some embodiments, it is contemplated that at least three distinct filter bodies **708**A-G are used. In further embodiments, between 10 and 1000 distinct filter bodies **708**A-G are used, including at least 10, at least 50, and/or at least 100 distinct filter bodies **608**A-G.

[0083] In still further embodiments, the plurality of filter bodies **308** can comprise repeating cycles of these distinct filter bodies **708**A-G such that the entire channel **404**, **704** and/or channel system **302** is filled with the plurality of filter bodies **308**. The plurality of filter bodies **308** can then be circulated through the channel system **302** via the liquid continuous phase **310** such that the repeating cycles of filter bodies **708**A-G are flowed over each light-sensitive element **402** of the sensor array **102**. Accordingly, it should be appreciated that in this manner, each light-sensitive element **402** of the sensor array **102** can continuously record light intensity data modulated by the flow filter **104** and ultimately recover a spectral signature for the imaging target **106**.

[0084] In some embodiments, such as the example shown in FIG. **7**B, the plurality of optically-active bodies **308** can include one or more calibration bodies **708**A. These calibration bodies **708**A may be configured to provide a reference signal used to normalize signal measurements or otherwise aid in spectral recovery.

[0085] In further embodiments, the flow filter **104** may also include one or more optically opaque spacers **706** as shown in the example of FIG. **8**. In embodiments, these opaque spacers **706** may be placed in between each optically-active body **308**. These opaque spacers **706** can be configured to block all light from reaching the light-sensitive elements **404** of the sensor array **104**. Thus, in this manner, the light-sensitive elements **404** may utilize event-based detection to record light intensity measurements based on the sudden changes in light intensity caused by the moving cycles of spacers **706** and optically-active bodies **308**.

[0086] In embodiments, the liquid continuous phase **310** may be pumped through the channel system **302** via the continuous phase pump **304** such that the plurality of filter bodies **308** have an average flow velocity in the microchannels **404** of from about 50 μm/s to about 50 cm/s, including about 0.5 cm/s.

[0087] Also described herein are methods of performing hyperspectral imaging of an imaging target. For example, with reference to FIG. **9**, an exemplary method **900** of hyperspectral imaging using a flow filter **104** is illustrated according to aspects of the present disclosure.

[0088] As shown, the method **900** can include, in a step **910**, directing the imaging optics **110** (e.g., a lens assembly, etc.) of the hyperspectral imaging system **100** towards an imaging target **106**.

[0089] When the imaging target **106** is ready to be imaged, the method **900** can then include, in a step **920**, flowing a plurality of optically-active bodies **308** through a microfluidic channel system **302** of the flow filter **104**.

[0090] While flowing the optically-active bodies **308** through the microfluidic channel system **302**, the method **900** can then include, in a step **930**, receiving light that is reflected and/or emitted by the imaging target projected to pass through one or more flowing optically-active bodies. In embodiments, this light (i.e., incident light L) is received through the imaging optics **110** of the hyperspectral imaging system **100**.

[0091] Then, the method **900** can include, in a step **940**, measuring signals from one or more of the plurality of light-sensitive elements **404**, **704** of a sensor array **102** that are generated when the received light, after passing through one or more flowing optically-active bodies, reaches the light-sensitive elements **402**, **702**. As described above, each of the light-sensitive elements **402**, **702** measures intensity data which can be used for spectral recovery.

[0092] In particular embodiments, the microfluidic channel system **302** is arranged relative to the sensor array **102** of the hyperspectral imaging system **100** such that the received light passes through one or more of the plurality of optically-active bodies **308** flowing within the microfluidic channel system **302** before reaching one or more of the plurality of light-sensitive elements of the sensor array **102**.

[0093] In embodiments, the sensor data collected by the light-sensitive elements **402**, **702** may also indicate spatial coordinates such that spatial and light intensity data is recorded. In further embodiments, this sensor data can be collected in a “snapshot” manner, i.e., over the course of several seconds or less. In other embodiments, sensor data may be collected over extended periods of time.

[0094] Once the sensor data is collected, the method **900** can include, in a step **950**, recovering spectral data (or spectral signature) for the imaging target **106** based on the measured signals. In embodiments, light intensity measurements may be processed and the spectral data recovered by one or more processors **202** of a hyperspectral imaging controller **112**. In particular embodiments, spectral data/signature may be recovered using a compressive sensing algorithm and/or a trained machine learning algorithm.

[0095] In particular, measurements of an optical spectrum, denoted by the vector x, where each entry is an intensity value at a wavelength or band of wavelengths, involves the measurement of multiple light intensities through more than one filtering element (e.g., the optically-active bodies **308**) with known spectral responses. These spectral responses can be assembled into a sensing matrix, denoted ¢, where each row corresponds to a filtering element and each entry within each row is an optical transmission value at a wavelength or range of wavelengths for the corresponding filtering element. The measured intensities through each filtering element can be assembled into a measurement vector, denoted y. The measurement process can be modeled according to Eqn. 1:

$$y=\Phi\text{.sub.X} \qquad (1)$$

where y has dimension N×1, where N is the total number of filtering elements (e.g., optically-active bodies **308**), Φ has dimension N×M, where M is the number of spectral response datapoints obtained for each filtering element, and x has a dimension of M×1.

[0096] It will be appreciated that the spectral accuracy will depend on the measurement and recovery processes. In practice, typically N<<M, and an inverse of Φ cannot be easily computed to determine x from y. Hence, signal recovery methods are necessary.

[0097] Accordingly, in one embodiment, the step **950** can include a signal recovery method such as compressive sensing (CS), which involves the recovery of x in a domain where it has a sparse representation. In this context, sparse refers to a mathematical property where most coefficients in a transformed basis are zero or near zero. Typically, optical spectra are not sparse. To express the signal in a sparse form, we assume following:

$$x_s = \Psi x \qquad (2)$$

where x_s is a sparse representation of x and Ψ is a transformation matrix (e.g., discrete cosine transform, wavelet transform, Fourier transform) suitable for enforcing sparsity. The recovery problem can then be framed as:

$$y = \Phi \Psi x \qquad (3)$$

where x_s (Ψx) is recovered using an optimization algorithm (e.g., basis pursuit).

[0098] Accordingly, x can then be recovered from x_s using the inverse of the transformation matrix:

$$x = \Psi^{-1} x_s \qquad (4)$$

[0099] According to another embodiment, the step **950** can include a signal recovery method involving the use of machine learning (ML) and/or artificial intelligence (AI). In this embodiment, y may be considered a latent representation of x, wherein a decoder structure is trained to recover x from y based on sets of training data representative of the spectra to be observed. The decoder architecture may include but is not limited to fully connected layers, skip connections, batch normalization layers, or attention mechanisms, and combinations thereof. The decoder may generally be expressed as a function like:

$$D(y) = x' \qquad (5)$$

where D(y) is the entire decoder process and x′ is its output.

[0100] The parameters of the decoder, which may include weights and/or biases, may be trained using gradient descent according to some objective function (e.g. mean squared error) which compares a true input spectrum, x, and its corresponding recovered spectrum, x′. In order to avoid overfitting and allow the network to generalize well to out-of-distribution data, many different input spectra (x vectors) should be used in training. When a suitably low error between the true and recovered spectra is reached, the network may be tested on a test set where this set is comprised of spectra the network has not been trained on. Nonlinearities may also be introduced through activation functions (e.g. ReLU, Leaky ReLU) and initialization of the network parameters may vary according to the activation function used and/or overall architecture. Careful choices of all of these aspects may significantly improve the performance of the network.

[0101] In order to enhance the robustness of the network, it is also possible to incorporate a probabilistic approach, especially to capture epistemic uncertainty. This could be done using, for example, a probabilistic decoder which samples from the latent space (y vector space) using an assumed variance, which could correspond to measurement noise. This network could be trained using the KL divergence objective function, wherein the recovered spectrum is pushed towards the true distribution given by the spectra inputted into the measurement process.

[0102] As described here, the signal recovery process is repeated for each pixel (i.e., light-sensitive element **402**) of the sensor array **102**. Based on the spatial information collected and knowledge of the sensor array **102**, spectral images may also be generated.

[0103] It should be appreciated that all combinations of the foregoing concepts and additional concepts discussed in greater detail below (provided such concepts are not mutually inconsistent) are contemplated as being part of the inventive subject matter disclosed herein. In particular, all combinations of claimed subject matter appearing at the end of this disclosure are contemplated as being part of the inventive subject matter disclosed herein. It should also be appreciated that terminology explicitly employed herein that also may appear in any disclosure incorporated by reference should be accorded a meaning most consistent with the particular concepts disclosed herein.

[0104] All definitions, as defined and used herein, should be understood to control over dictionary definitions, definitions in documents incorporated by reference, and/or ordinary meanings of the defined terms.

[0105] The indefinite articles “a” and “an,” as used herein in the specification and in the claims, unless clearly indicated to the contrary, should be understood to mean “at least one.”

[0106] The phrase “and/or,” as used herein in the specification and in the claims, should be understood to mean “either or both” of the elements so conjoined, i.e., elements that are conjunctively present in some cases and disjunctively present in other cases. Multiple elements listed with “and/or” should be construed in the same fashion, i.e., “one or more” of the elements so conjoined. Other elements may optionally be present other than the elements specifically identified by the “and/or” clause, whether related or unrelated to those elements specifically identified.

[0107] As used herein in the specification and in the claims, “or” should be understood to have the same meaning as “and/or” as defined above. For example, when separating items in a list, “or” or “and/or” shall be interpreted as being inclusive, i.e., the inclusion of at least one, but also including more than one, of a number or list of elements, and, optionally, additional unlisted items. Only terms clearly indicated to the contrary, such as “only one of” or “exactly one of,” or, when used in the claims, “consisting of,” will refer to the inclusion of exactly one element of a number or list of elements. In general, the term “or” as used herein shall only be interpreted as indicating exclusive alternatives (i.e. “one or the other but not both”) when preceded by terms of exclusivity, such as “either,” “one of,” “only one of,” or “exactly one of.”

[0108] As used herein in the specification and in the claims, the phrase “at least one,” in reference to a list of one or more elements, should be understood to mean at least one element selected from any one or more of the elements in the list of elements, but not necessarily including at least one of each and every element specifically listed within the list of elements and not excluding any combinations of elements in the list of elements. This definition also allows that elements may optionally be present other than the elements specifically identified within the list of elements to which the phrase “at least one” refers, whether related or unrelated to those elements specifically identified.

[0109] As used herein, although the terms first, second, third, etc. may be used herein to describe various elements or components, these elements or components should not be limited by these terms. These terms are only used to distinguish one element or component from another element or component. Thus, a first element or component discussed below could be termed a second element or component without departing from the teachings of the inventive concept.

[0110] Unless otherwise noted, when an element or component is said to be “connected to,” “coupled to,” or “adjacent to” another element or component, it will be understood that the element or component can be directly connected or coupled to the other element or component, or intervening elements or components may be present. That is, these and similar terms encompass cases where one or more intermediate elements or components may be employed to connect two elements or components. However, when an element or component is said to be “directly connected” to another element or component, this encompasses only cases where the two elements or components are connected to each other without any intermediate or intervening elements or components.

[0111] In the claims, as well as in the specification above, all transitional phrases such as “comprising,” “including,” “carrying,” “having,” “containing,” “involving,” “holding,” “composed of," and the like are to be understood to be open-ended, i.e., to mean including but not limited to. Only the transitional phrases "consisting of" and "consisting essentially of" shall be closed or semi-closed transitional phrases, respectively.

[0112] It should also be understood that, unless clearly indicated to the contrary, in any methods claimed herein that include more than one step or act, the order of the steps or acts of the method is not necessarily limited to the order in which the steps or acts of the method are recited.

[0113] The above-described examples of the described subject matter can be implemented in any of numerous ways. For example, some aspects can be implemented using hardware, software or a combination thereof. When any aspect is implemented at least in part in software, the software code can be executed on any suitable processor or collection of processors, whether provided in a single device or computer or distributed among multiple devices/computers.

[0114] The present disclosure can be implemented as a system, a method, and/or a computer program product at any possible technical detail level of integration. The computer program product can include a computer readable storage medium (or media) having computer readable program instructions thereon for causing a processor to carry out aspects of the present disclosure.

[0115] A computer readable storage medium can be a tangible device that can retain and store instructions for use by an instruction execution device. The computer readable storage medium can be, for example, but is not limited to, an electronic storage device, a magnetic storage device, an optical storage device, an electromagnetic storage device, a semiconductor storage device, or any suitable combination of the foregoing. A non-exhaustive list of more specific examples of the computer readable storage medium comprises the following: a portable computer diskette, a hard disk, a random access memory (RAM), a read-only memory (ROM), an erasable programmable read-only memory (EPROM or Flash memory), a static random access memory (SRAM), a portable compact disc read-only memory (CD-ROM), a digital versatile disk (DVD), a memory stick, a floppy disk, a mechanically encoded device such as punch-cards or raised structures in a groove having instructions recorded thereon, and any suitable combination of the foregoing. A computer readable storage medium, as used herein, is not to be construed as being transitory signals per se, such as radio waves or other freely propagating electromagnetic waves, electromagnetic waves propagating through a waveguide or other transmission media (e.g., light pulses passing through a fiber-optic cable), or electrical signals transmitted through a wire.

[0116] Computer readable program instructions described herein can be downloaded to respective computing/processing devices from a computer readable storage medium or to an external computer or external storage device via a network, for example, the Internet, a local area network, a wide area network and/or a wireless network. The network can comprise copper transmission cables, optical transmission fibers, wireless transmission, routers, firewalls, switches, gateway computers and/or edge servers. A network adapter card or network interface in each computing/processing device receives computer readable program instructions from the network and forwards the computer readable program instructions for storage in a computer readable storage medium within the respective computing/processing device.

[0117] Computer readable program instructions for carrying out operations of the present disclosure can be assembler instructions, instruction-set-architecture (ISA) instructions, machine instructions, machine dependent instructions, microcode, firmware instructions, state-setting data, configuration data for integrated circuitry, or either source code or object code written in any combination of one or more programming languages, comprising an object oriented programming language such as Smalltalk, C++, or the like, and procedural programming languages, such as the "C" programming language or similar programming languages. The computer readable program instructions can execute entirely on the user's computer, partly on the user's computer, as a stand-alone software package, partly on the user's computer and partly on a remote computer or entirely on the remote computer or server. In the latter scenario, the remote computer can be connected to the user's computer through any type of network, comprising a local area network (LAN) or a wide area network (WAN), or the connection can be made to an external computer (for example, through the Internet using an Internet Service Provider). In some examples, electronic circuitry comprising, for example, programmable logic circuitry, field-programmable gate arrays (FPGA), or programmable logic arrays (PLA) can execute the computer readable program instructions by utilizing state information of the computer readable program instructions to personalize the electronic circuitry, in order to perform aspects of the present disclosure.

[0118] Aspects of the present disclosure are described herein with reference to flowchart illustrations and/or block diagrams of methods, apparatus (systems), and computer program products according to examples of the disclosure. It will be understood that each block of the flowchart illustrations and/or block diagrams, and combinations of blocks in the flowchart illustrations and/or block diagrams, can be implemented by computer readable program instructions.

[0119] The computer readable program instructions can be provided to a processor of a, special purpose computer, or other programmable data processing apparatus to produce a machine, such that the instructions, which execute via the processor of the computer or other programmable data processing apparatus, create means for implementing the functions/acts specified in the flowchart and/or block diagram block or blocks. These computer readable program instructions can also be stored in a computer readable storage medium that can direct a computer, a programmable data processing apparatus, and/or other devices to function in a particular manner, such that the computer readable storage medium having instructions stored therein comprises an article of manufacture comprising instructions which implement aspects of the function/act specified in the flowchart and/or block diagram or blocks.

[0120] The computer readable program instructions can also be loaded onto a computer, other programmable data processing apparatus, or other device to cause a series of operational steps to be performed on the computer, other programmable apparatus or other device to produce a computer implemented process, such that the instructions which execute on the computer, other programmable apparatus, or other device implement the functions/acts specified in the flowchart and/or block diagram block or blocks.

[0121] The flowchart and block diagrams in the Figures illustrate the architecture, functionality, and operation of possible implementations of systems, methods, and computer program products according to various examples of the present disclosure. In this regard, each block in the flowchart or block diagrams can represent a module, segment, or portion of instructions, which comprises one or more executable instructions for implementing the specified logical function(s). In some alternative implementations, the functions noted in the blocks can occur out of the order noted in the Figures. For example, two blocks shown in succession can, in fact, be executed substantially concurrently, or the blocks can sometimes be executed in the reverse order, depending upon the functionality involved. It will also be noted that each block of the block diagrams and/or flowchart illustration, and combinations of blocks in the block diagrams and/or flowchart illustration, can be implemented by special purpose hardware-based systems that perform the specified functions or acts or carry out combinations of special purpose hardware and computer instructions.

[0122] Other implementations are within the scope of the following claims and other claims to which the applicant can be entitled.

[0123] While several inventive embodiments have been described and illustrated herein, those of ordinary skill in the art will readily envision a variety of other means and/or structures for performing the function and/or obtaining the results and/or one or more of the advantages described herein, and each of such variations and/or modifications is deemed to be within the scope of the inventive embodiments described herein. More generally, those skilled in the art will readily appreciate that all parameters, dimensions, materials, and configurations described herein are meant to be exemplary and that the actual parameters, dimensions, materials, and/or configurations will depend upon the specific application or applications for which the inventive teachings is/are used.

Those skilled in the art will recognize, or be able to ascertain using no more than routine experimentation, many equivalents to the specific inventive embodiments described herein. It is, therefore, to be understood that the foregoing embodiments are presented by way of example only and that, within the scope of the appended claims and equivalents thereto, inventive embodiments may be practiced otherwise than as specifically described and claimed. Inventive embodiments of the present disclosure are directed to each individual feature, system, article, material, kit, and/or method described herein. In addition, any combination of two or more such features, systems, articles, materials, kits, and/or methods, if such features, systems, articles, materials, kits, and/or methods are not mutually inconsistent, is included within the inventive scope of the present disclosure.

Claims

1. A hyperspectral imaging system comprising: a flow filter comprising a plurality of optically-active bodies and a microfluidic channel system, the microfluidic channel system defining a flow path for the plurality of optically-active bodies; and a sensor array comprising a plurality of light-sensitive elements, wherein each light-sensitive sensor is configured to measure the intensity of light that is reflected and/or emitted by an imaging target located outside of the imaging system, the light having been modified by the optically-active bodies within the flow filter; wherein the microfluidic channel system of the flow filter is arranged relative to the sensor array such that the light that is reflected and/or emitted by the imaging target passes through the microfluidic channel system before reaching one or more of the plurality of light-sensitive elements.
2. The hyperspectral imaging system of claim 1, wherein the plurality of optically-active bodies comprises at least three filter bodies having distinct optical characteristics over a desired spectrum, and wherein the distinct optical characteristics include at least one of a distinct absorbance curve and/or a distinct photoluminescence curve.
3. The hyperspectral imaging system of claim 2, wherein the plurality of optically-active bodies comprises a repeating sequence of the at least three filter bodies.
4. The hyperspectral imaging system of claim 2, wherein the plurality of optically-active bodies comprises at least fifty filter bodies having distinct optical characteristics over the desired spectrum.
5. The hyperspectral imaging system of claim 1, wherein the flow filter further comprises: a liquid continuous phase; and a continuous phase pump fluidly connected to the microfluidic channel system; and wherein the continuous phase pump is configured to pump the liquid continuous phase through the microfluidic channel system, and wherein the plurality of optically-active bodies are carried through the microfluidic channel system by the liquid continuous phase.
6. The hyperspectral imaging system of claim 4, wherein the plurality of optically-active bodies are ordered sequentially and carried sequentially through the microfluidic channel system.
7. The hyperspectral imaging system of claim 1, wherein each optically-active body of the plurality of optically-active bodies comprises a body medium and an optically-active component contained within the body medium.
8. The hyperspectral imaging system of claim 7, wherein the optically-active component comprises a plurality of quantum dots.
9. The hyperspectral imaging system of claim 8, wherein the plurality of optically-active bodies comprises at least three filter bodies having distinct optical characteristics over a desired spectrum, wherein the distinct optical characteristics include at least one of a distinct absorbance curve and/or a distinct photoluminescence curve, and wherein the optically-active component of each of the at least three filter bodies comprises quantum dots having a different size, shape, and/or composition.
10. The hyperspectral imaging system of claim 7, wherein the body medium comprises a liquid that is immiscible with the liquid continuous phase.

11. The hyperspectral imaging system of claim 7, wherein the body medium comprises at least one of a solid, a semi-solid, a gel, and a liquid polymer material.
12. The hyperspectral imaging system of claim 1, wherein the flow filter further comprises one or more optically opaque spacers disposed between each of the plurality of optically-active bodies.
13. The hyperspectral imaging system of claim 1, further comprising a hyperspectral imaging controller, wherein the hyperspectral imaging controller comprises: one or more processors; and a non-transitory computer-readable memory storing instructions that, when executed by the one or more processors, causes the hyperspectral imaging controller to perform one or more of the following operations: generating sensor data using the sensor array based on the light that is reflected and/or emitted by the imaging target, wherein the sensor data comprises, for each light-sensitive element of the sensor array, a plurality of light intensity measurements; and recovering a spectral signature for the imaging target based on the sensor data generated, wherein the spectral signature is recovered using a compressive sensing algorithm and/or a trained machine learning algorithm.
14. A flow filter for moderating light, the flow filter comprising: a plurality of optically-active bodies, wherein each optically-active body comprises a body medium and an optically-active component contained within the body medium; a microfluidic channel system defining a flow path for the plurality of optically-active bodies; a liquid continuous phase configured to carry the plurality of optically-active bodies through the microfluidic channel system along the flow path; and a continuous phase pump fluidly connected to the microfluidic channel system, wherein the continuous phase pump is configured to pump the liquid continuous phase through the microfluidic channel system such that the liquid continuous phase carries the plurality of optically-active bodies through the microfluidic channel system along the flow path.
15. The flow filter of claim 14, wherein the plurality of optically-active bodies comprises at least three filter bodies having distinct optical characteristics over a desired spectrum, wherein the distinct optical characteristics include at least one of a distinct absorbance curve and/or a distinct photoluminescence curve, wherein the optically-active component of the plurality of optically-active bodies comprises a plurality of quantum dots, and wherein each of the at least three filter bodies comprise quantum dots having a different size, shape, and/or composition.
16. The flow filter of claim 14, wherein the body medium of the plurality of optically-active bodies comprises a liquid that is immiscible with the liquid continuous phase, and/or wherein the body medium of the plurality of optically-active bodies comprises a solid, a semi-solid, a gel, and a liquid polymer material.
17. The flow filter of claim 14, wherein the plurality of optically-active bodies are ordered sequentially and carried sequentially through the microfluidic channel system.
18. A method of hyperspectral imaging using a hyperspectral imaging system comprising a lens, a flow filter, a sensor array having a plurality of light-sensitive elements, and a hyperspectral imaging controller, the method comprising: directing the lens of the hyperspectral imaging system towards an imaging target; flowing a plurality of optically-active bodies through a microfluidic channel system of the flow filter; receiving, through the lens of the hyperspectral imaging system, light that is reflected and/or emitted by the imaging target; and measuring signals from one or more of the plurality of light-sensitive elements of the sensor array based on the light that is reflected and/or emitted by the imaging target and filtered by one or more optically-active bodies of the plurality of optically-active bodies; and recovering, via one or more processors of the hyperspectral imaging controller, a spectral data for the imaging target based on the measured signals; wherein the microfluidic channel system is arranged relative to the sensor array such that the received light that is reflected and/or emitted by the imaging target is passed through one or more of the plurality of optically-active bodies flowing within the microfluidic channel system before reaching one or more of the plurality of light-sensitive elements of the sensor array.
19. The method of claim 18, wherein the plurality of optically-active bodies comprises at least

three filter bodies having distinct optical characteristics over a desired spectrum, wherein the distinct optical characteristics include at least one of a distinct absorbance curve and/or a distinct photoluminescence curve, and wherein the measured signals include light intensity measurements corresponding to the received light that has passed through each of the at least three filter bodies.

20. The method of claim 18, wherein each optically-active body of the plurality of optically-active bodies comprises a body medium and an optically-active component contained within the body medium, wherein the optically-active component comprises a plurality of quantum dots, and wherein the plurality of optically-active bodies are ordered sequentially and flowed sequentially through the microfluidic channel system.