

SPECTROFILOMETER

CROSS-REFERENCE TO RELATED APPLICATION

This application claims priority to U.S. Provisional Patent Application No.
5 63/236,896, filed on August 25, 2021, the disclosure of which is incorporated by
reference herein in its entirety.

FIELD OF THE INVENTION

The present invention relates to spectrometers, spectroscopes, radiometers,
10 interferometers, profilometers and particularly, but not exclusively, to optical
spectrofilometers.

BACKGROUND OF THE INVENTION

Interferometers and spectrometers are used in a variety of disciplines to measure
15 the properties of electromagnetic radiation, such as light. They are used to measure various
properties of the radiation, such as, for example, its intensity, polarization, wavelength,
frequency, or phase.

Profilometers are used in a variety of disciplines for the evaluation or measurement
of profile features, for example, surface roughness, waviness, feature height, smoothness,
20 void detection and defect detection.

Interferometers, spectrometers and profilometers may be considered
electromagnetic wave-processing systems, which collect electromagnetic radiation,
manipulate the collected electromagnetic radiation to generate a pattern from the
electromagnetic radiation, detect the generated pattern formed from the collected and
25 manipulated electromagnetic radiation, and generate a signal in response to detecting the
detected pattern. The elements of the interferometers, spectrometers and profilometers
may be static or dynamic and their elements may be mounted so as to allow them to be
statically or dynamically scanned or translated.

In some interferometer systems, electromagnetic radiation is passed through a Young's slits arrangement to form two or more sources of secondary radiation that diffract as the sources exit the slits and then interfere as they overlap. The interference pattern is then detected as an interferogram, which is a spatial representation of the interference pattern. The form of the interferogram is determined by the spectral components of the diffracted light.

In some spectrometer systems, electromagnetic radiation is passed through a diffraction grating and imaging arrangement to form multiple secondary sources of radiation that diffract as they exit the slits and then interfere as they overlap. The interference pattern is then detected as a spectrogram, which is a spatial representation of the interference pattern. The form of the spectrogram is determined by the spectral components of the diffracted light.

In some profilometer systems, patterns of electromagnetic radiation are projected onto the surface of interest and the reflected patterns of electromagnetic radiation from the surface of interest are detected as an image pattern profile map representation of the surface. The form of the profile map is determined by the patterns of the reflected light.

Detector arrays are commonly used to record and capture interferogram, spectrogram, and image patterns for signal processing and analysis. A range of image analysis, frequency analysis, mathematical transforms, fringe counting, machine vision, and weighting algorithms are commonly used to analyze the patterns to recover amplitude, intensity, temporal information, spectral information, profile information and/or phase information, among other data.

Interferometers, spectrometers and profilometers are typically used independently and do not share the same housing, optics, or detection elements, and the generated and detected patterns in interferometer, spectrometer and profilometer instruments typically differ largely in distributed frequency and amplitude. For example, considering low-coherence sources, the interference pattern produced using a wavefront interferometer contains a small number of high frequency oscillations over a narrow extent, whereas the spectral pattern contains a large number of low frequency oscillations over a wide extent. The converse is respectively true for a high-coherence source. Profilometer projection patterns can vary dramatically in amplitude, frequency, phase and polarization.

Interferometers are typically best operated in single-mode for highest visibility, fidelity, and resolution such that the collection of low-coherence light is limited due to the wide vector variance nature of such light, whereas spectrometer instruments are significantly less limited. Spectrometers are susceptible to saturation when operated with high-coherence light as the narrow vector variance nature of the laser light results in most of the light illuminating only one or few pixels driving them into saturation, whereas wavefront interferometers disperse the laser light over most of the pixels in the array. Profilometer imaging patterns are also typically dispersed over most of the pixels in the array over a range of pattern feature frequencies and intensities.

For at least these reasons, there is a need for improved spectrofilometers that avoid these limitations.

SUMMARY OF THE INVENTION

According to an aspect of the present disclosure, a spectrofilometer is provided. The spectrofilometer includes an enclosure, at least one profilometer and one or more interferometer beam-splitting elements and/or one or more spectrometer beam-dispersing elements. The at least one profilometer and one or more interferometer beam-splitting elements and/or the one or more spectrometer beam-dispersing elements are housed in the enclosure, share one or more radiation sensitive elements, which are arranged to generate a signal in response to incident electromagnetic radiation, and each generate one or more optical outputs. The one or more optical outputs are arranged such that respective optical axes intersect substantially in a plane of the one or more radiation sensitive elements.

According to various aspects, the spectrofilometer may further include one or more reflective surfaces between the optical outputs.

According to various aspects, the one or more reflective surfaces include one or more optical coatings on one or more of the surfaces.

According to various aspects, the one or more of the reflective surfaces are microelectromechanical systems (MEMS) elements. Each of the MEMS elements are controllable and are configured to reflect a portion of the incident electromagnetic radiation.

According to various aspects, the one or more radiation sensitive elements are configured to detect one or more inputs originating from one or more spatially distinct locations.

According to various aspects, the one or more inputs include the one or more optical
5 outputs from at least one profilometer and one or more interferometer beam-splitting elements and/or one or more spectrometer beam-dispersing elements.

According to various aspects, the one or more inputs include one or more imaging bundles.

According to various aspects, the one or more inputs include one or more optical
10 waveguides.

According to various aspects, the one or more optical waveguides include one or more optical fibers.

According to various aspects, wherein the spectrofilometer further includes one or more optical waveguides.

According to various aspects, the one or more optical waveguides include one or
15 more optical fibers.

According to various aspects, the one or more optical fibers include one or more of: microstructured optical fibers; and multicore optical fibers.

According to various aspects, the one or more interferometer beam-splitting
20 elements are dynamically adjustable.

According to various aspects, the one or more spectrometer beam-dispersing elements are dynamically adjustable.

According to various aspects, the spectrofilometer further includes one or more processors, and a memory. The memory is configured to store instructions which, when
25 executed by the one or more processors, cause the one or more processors to process one or more signals generated by the one or more radiation sensitive elements, and generate a spatial intensity profile of the incident electromagnetic radiation.

According to various aspects, the instructions, when executed by the one or more processors, further cause the one or more processors to recover data from the spatial
30 intensity profile using one or more of: transform processing techniques; curve fitting techniques; frequency filtering techniques; fringe counting techniques; interpolation

techniques; weighting techniques; one or more orders of differentiation; one or more orders of integration; predictive analysis techniques; machine learning techniques; and artificial intelligence techniques. The data includes one or more of: temporal data; spectral data; phase data; amplitude data; and polarization data.

5 According to another aspect of the present disclosure, a method of analyzing electromagnetic radiation is provided. The method includes providing a spectrofilometer. The spectrofilometer includes an enclosure, a processor, a memory, at least one profilometer and one or more interferometer beam-splitting elements, and/or one or more spectrometer beam-dispersing elements. The at least one profilometer and one or more
10 interferometer beam-splitting elements and/or the one or more spectrometer beam-dispersing elements are housed in the enclosure, share one or more radiation sensitive elements, which are arranged to generate a signal in response to incident electromagnetic radiation, and each generate one or more optical outputs. The one or more optical outputs are arranged such that respective optical axes intersect substantially in a plane of the one
15 or more radiation sensitive elements. The method further includes processing, using the processor, one or more signals generated by the one or more radiation sensitive elements, and generating a spatial intensity profile of the incident electromagnetic radiation.

 According to various embodiments, the method further includes recovering, using the processor, data from the spatial intensity profile using transform processing techniques,
20 curve fitting techniques, frequency filtering techniques, fringe counting techniques, interpolation techniques, weighting techniques, one or more orders of differentiation, one or more orders of integration, predictive analysis techniques, phase analysis techniques, machine learning techniques, and/or artificial intelligence techniques. The data includes one or more of: temporal data; spectral data; phase data; frequency data; amplitude data;
25 and polarization data.

Further features and advantages of the invention will become apparent from the following description of preferred embodiments of the invention, given by way of example only, which is made with reference to the accompanying drawings.

5

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other features of the present disclosure will become more fully apparent from the following description and appended claims, taken in conjunction with the accompanying drawings. Understanding that these drawings depict only several examples in accordance with the disclosure and are, therefore, not to be considered limiting
10 of its scope, the disclosure will be described with additional specificity and detail through use of the accompanying drawings, in which:

FIG. 1 is a schematic diagram of a known wavefront interferometer;

FIG. 2 is a schematic diagram of a known diffraction grating spectrometer;

FIG. 3 is a schematic diagram of a known profilometer; and

15

FIG. 4 is a schematic diagram of a spectrofilometer according to an embodiment of the present disclosure.

DETAILED DESCRIPTION OF THE INVENTION

In the following detailed description, reference is made to the accompanying
20 drawings, which form a part hereof. In the drawings, similar symbols typically identify similar components, unless context dictates otherwise. The illustrative examples described in the detailed description, drawings, and claims are not meant to be limiting. Other examples may be utilized, and other changes may be made, without departing from the spirit or scope of the subject matter presented herein. It will be readily understood that the
25 aspects of the present disclosure, as generally described herein, and illustrated in the figures, can be arranged, substituted, combined, separated, and designed in a wide variety of different configurations, all of which are implicitly contemplated herein.

As used in this document, the singular forms “a,” “an,” and “the” include plural references unless the context clearly dictates otherwise. Unless defined otherwise, all
30 technical and scientific terms used herein have the same meanings as commonly

understood by one of ordinary skill in the art. When used in this document, the term “comprising” (or “comprises”) means “including (or includes), but not limited to.” When used in this document, the term “exemplary” is intended to mean “by way of example” and is not intended to indicate that a particular exemplary item is preferred or required.

5 In this document, the term “approximately,” when used in connection with a numeric value, is intended to include values that are close to, but not exactly, the number. For example, in some embodiments, the term “approximately” may include values that are within +/- 10 percent of the value.

10 Various embodiments of the present disclosure pertain to the simultaneous capturing and recording of synchronized data sets of multiple different signal types and derivative information from different signal types including, but not limited to, spectral data, interference data, image data, and/or related data. According to various embodiments, simultaneous collection and imaging of low-coherence, low-intensity light onto a shared detector array using a spectrogram-generating system, and collecting and imaging high-
15 coherence, high-intensity light onto a shared detector array using an interferogram-generating system are provided. In example embodiments, collection and imaging light from multiple locations and/or from multiple instruments onto a shared detector array are also provided.

Referring now to FIG. 1, a schematic diagram of an example prior art interferometer
20 **100**, based upon a fiber-optic interferometer, is illustratively depicted.

As shown in FIG. 1, the interferometer **100** includes an input aperture. The aperture may be a waveguide arm **102** having a fiber-optic input port **102a**, a 1x2 fiber-optic coupler/splitter **104**, and two output fiber-optic waveguide arms **106a**, **106b**. Each of the two output fiber-optic waveguide arms **106a**, **106b** has a fiber-optic optical output port
25 **108a**, **108b**. Each of the waveguide arms may include a core region surrounded by a cladding region having a refractive index lower than the core region. The output ports **108a**, **108b** are separated by a distance, **d**. According to various embodiments, the distance, **d**, is approximately between 1 to 10 mm.

Each wavelength of light being transmitted in a given waveguide arm **102**, **106a**,
30 **106b** exists as an optical mode. Each mode typically exhibits a particular spatial extent and has a characteristic mode profile that is dependent on the waveguide parameter of the

waveguide arm **102**, **106a**, **106b**. The waveguide parameter is dependent on the relative refractive indices and dimensions of the core and cladding regions and the wavelength of light being transmitted. Each of the fiber-optic waveguide arms **102**, **106a**, and **106b** is a single mode waveguide arm for wavelengths longer than a certain minimum wavelength
5 corresponding to a highest frequency of light for which the interferometer **100** is designed to work.

The interferometer **100** includes a splitter **104** that is configured to split the light received at the input port **102a** substantially equally between the two output ports **108a**, **108b**.

10 According to an example of use of the interferometer **100**, electromagnetic radiation, **E**, such as light that is to be analyzed, is received by (i.e., coupled into) the input port **102a** of the input waveguide arm **102** and split, by the splitter **104**, between the output waveguide arms **106a**, **106b**. The split light emerges, respectively, from the two output ports **108a**, **108b**. The emerging light diffracts and interferes to form a characteristic
15 interference pattern that illuminates, and can be detected by, a detector **110**, which is spaced apart by a distance, **Z**, from the output ports **108a**, **108b**. The detector **110** may be, for example, an array of individual photosensitive detector elements (pixels) **112**, such as a charge-coupled device (CCD) detector array.

Each of the output ports **108a**, **108b** includes a numerical aperture, which can be
20 wavelength dependent and relates to the relative refractive indices of a waveguide core region and a waveguide cladding region, as well as the physical size of the waveguide core. Light emerging from the output ports **108a**, **108b** will diffract into the surrounding medium (typically air) with a divergence angle that depends on the numerical aperture of the respective output port **108a**, **108b**. Typically, each of the output ports **108a**, **108b** has the
25 same numerical aperture for a given wavelength.

As the two diffracted beams emerge from the output ports **108a**, **108b** and propagate and diverge, the beams spatially overlap such that the fields of the wave fronts interfere. The fields, due to the overlapping beams, provide an intensity variation that depends on a relative optical path delay difference, which is, in turn, dependent on the
30 wavelength of the emerging light. This intensity variation in a given plane is an interference fringe pattern that is characteristic of the emerging light. The delay difference

evolves across the detector surface **110** to form the interference fringes and is used to form an interferogram, which is a spatially or temporally dependent image or representation of the light intensity variation in the plane of the detector **110**.

Each of the elements **112** of the detector **110** is arranged, for example, to generate
5 a charge signal proportional to the intensity of light incident on the element **112**, such that the detector **110** can be used to measure the interference pattern and form the interferogram. Typically, the interferometer **100** is arranged such that at least two elements **112** of the detector **110** detect light from each interference fringe in order that the spatial sampling rate is at least twice the spatial periodicity of the interference fringe pattern. This enables
10 the interferometer **100** to satisfy the Nyquist sampling criterion and provide a lossless measurement of the fringe periodicity.

Typically, the interferogram is processed by either dedicated processing electronics (not shown), or a computer programmed with suitable processing software that receives a digital representation of the interferogram. The processing electronics or computer reads
15 the charge signals from the detector to form a spatial intensity profile, thus capturing an image of the interference fringes (the interferogram) at a rate above the Nyquist rate. The processing electronics or processing software may then process the captured spatial image data using, for example, one or more of mathematical transform processing, Fourier Transform processing, Hilbert Transform processing and statistical analysis, fringe
20 counting and weighting, or any other suitable processing technique, to analyze the spatially dependent intensity pattern. This enables characterization of the light illuminating the interferometer **100** and enables temporal and/or spectral and/or phase and/or amplitude and/or polarization information to be recovered.

Referring now to FIG. 2, a schematic diagram of an example of one type of prior
25 art spectrometer **200**, based upon a transmission diffraction grating spectrometer, is illustratively depicted.

The spectrometer **200** includes an input aperture that may be a waveguide arm **202** having a fiber-optic input port **202a** and a transmission diffraction grating **204**. Additional beam-shaping, collimating, and filtering optics may be included for example but for
30 simplicity they are not shown here.

The diffraction grating **204** interrupts the light incident on it and splits the light via the grating lines **206** and emits multiple secondary wavefronts **208**.

According to an example of use of the spectrometer **200**, electromagnetic radiation, **E**, such as light that is to be analyzed, is received by (i.e., coupled into) the input port **202a**
5 of the input waveguide arm **202** and interrupted by the lines **206** of the diffraction grating **204**, causing multiple secondary output wavefronts of light **208** to emerge, respectively, from the diffraction grating **204**. The emerging light diffracts and interferes to form a characteristic diffraction interference pattern that illuminates, and can be detected by, a detector **110**. The detector **110** may be, for example, an array of individual photosensitive
10 detector elements (pixels) **112**, such as a CCD detector array.

Each of the outputs **208** from the diffraction grating lines **206** has a numerical aperture, which, respectively, can be wavelength dependent and can relate material index properties as well as the physical sizes. Light emerging from the lines **206** diffracts into the surrounding medium (typically air) with a divergence angle that depends on the
15 numerical aperture of the respective lines. Typically, the grating lines will be uniform so each line of the lines **206** has the same numerical aperture for a given wavelength.

As the beams diffract outward from the diffraction grating **204**, they, respectively, propagate and diverge, and the beams spatially overlap such that the fields of the wavefronts interfere. The fields, due to the overlapping beams, provide an intensity
20 variation that depends on a relative optical path delay differences which is, in turn, dependent on the wavelength of the emerging light. This intensity variation in a given plane is an interference fringe pattern that is known as a diffraction pattern that is characteristic of the emerging light. The delay difference evolves across the detector surface **110** to form the interference fringes and is used to form a diffraction pattern, which
25 is a spatially- or temporally-dependent image or representation of the light intensity variation in the plane of the detector **110**.

Each of the elements **112** of the detector **110** is arranged, for example, to generate a charge signal proportional to the intensity of light incident on the element **112**, such that the detector **110** can be used to measure the diffraction pattern and infer a spectrum. For
30 broad band operation, the spectrometer **200** is typically arranged such that each wavelength

of light is confined to one or few of the elements **112** of the detector **110** to optimize the number of wavelengths that can be detected and resolved in the spectrum of incident light.

Typically, the diffraction pattern is processed by either dedicated processing electronics (not shown), or a computer programmed with suitable processing software that receives a digital representation of the interferogram. The processing electronics or computer reads the charge signals from the detector to form a spatial intensity profile, thus capturing an image of the diffraction pattern. The processing electronics or processing software may then process the captured spatial image data using, for example, one or more of fringe counting and weighting, transform processing, or any other suitable processing technique, to analyze the spatially dependent intensity pattern. This enables characterization of the light illuminating the spectrometer **200** and enables spectral information to be recovered that may be further analyzed and processed.

15

Referring now to FIG. 3, a schematic diagram of an example of one type of prior art profilometer **300**, based upon an image pattern projection system profilometer, is illustratively depicted.

The profilometer **300** includes an image pattern projection system **302** that illuminates the object of interest **304**. The object of interest **304** reflects the incident image pattern from multiple points **306** and the reflection pattern **308** from the object is incident on detector **110**.

Additional collection, beam-shaping, collimating, polarizing and filtering optics may be included for example but for simplicity they are not shown here. The reflected light forms a characteristic pattern which is a spatially- and/or temporally-dependent image or representation of the light intensity variation in the plane of the detector **110**. The detector **110** may be, for example, an array of individual photosensitive detector elements (pixels) **112**, such as a CCD detector array.

Each of the elements **112** of the detector **110** is arranged, for example, to generate a charge signal proportional to the intensity of light incident on the element **112**, such that the detector **110** can be used to measure the reflection pattern and infer a profile.

Typically, the reflection pattern is processed by either dedicated processing electronics (not shown), or a computer programmed with suitable processing software that receives a digital representation of the interferogram. The processing electronics or computer reads the charge signals from the detector to form a spatial intensity profile, thus capturing an image of the reflected pattern. The processing electronics or processing software may then process the captured spatial image data using, for example, one or more of fringe counting and weighting, transform processing, phase analysis, or any other suitable processing technique, to analyze the spatially dependent intensity pattern. This enables characterization of the light illuminating the object **304** and enables profile information to be recovered that may be further analyzed and processed.

Referring now to FIG. 4, a schematic diagram showing an exemplary embodiment of a spectrofilometer **400** is illustratively depicted, in accordance with various embodiments of the present disclosure.

The spectrofilometer **400** includes at least one profilometer image pattern projection system **430** and one or more interferometer beam-splitting elements **420** and/or one or more spectrometer beam-dispersing elements **425**. According to some embodiments, the spectrofilometer **400** includes at least one profilometer image pattern projection system **430** and one or more interferometer beam splitting elements **420**. According to some embodiments, the spectrofilometer **400** includes at least one profilometer image pattern projection system **430** and one or more spectrometer beam-dispersing elements **425**. According to various embodiments, the one or more interferometer beam-splitting elements **420** and/or the one or more spectrometer beam-dispersing elements **425** are housed within an enclosure **415**.

The at least one profilometer and one or more interferometer beam-splitting elements **420** and/or the one or more spectrometer beam-dispersing elements **425** share one or more radiation sensitive elements **112**, which are arranged to generate a signal in response to incident electromagnetic radiation, and are configured to generate one or more optical outputs. The one or more optical outputs are arranged such that respective optical axes intersect substantially in a plane of the one or more radiation sensitive elements.

According to various embodiments, the spectrofilometer **400** includes one or more reflective surfaces between optical outputs. The one or more reflective surfaces include

one or more optical coatings on one or more of the surfaces. The one or more reflective surfaces can include one or more microelectromechanical systems (MEMS) elements. According to various embodiments, each of the MEMS elements are controllable and are configured to reflect a portion of the incident electromagnetic radiation.

5 According to various embodiments, the one or more radiation sensitive elements are configured to detect one or more inputs originating from one or more spatially distinct locations. The one or more inputs include the one or more optical outputs from the one or more interferometer beam-splitting elements and/or the one or more spectrometer beam-dispersing elements. In some embodiments, the one or more inputs include one or more
10 imaging bundles. In some embodiments, the one or more inputs include one or more optical waveguides. The one or more optical waveguides can include one or more optical fibers. The one or more optical fibers can include microstructured optical fibers, multicore optical fibers, and/or other suitable forms of optical fiber.

 The spectrofilometer **400** includes one or more input apertures that may be
15 waveguide arms **102**, **202**, a fiber-optic coupler/splitter **104** that may be 1x2, nx2, 1xn or nxn, and output fiber-optic waveguide arms **106a**, **106b**, each having a fiber-optic optical output port **108a**, **108b**. Each of the waveguide arms includes a core region surrounded by a cladding region having a refractive index lower than the core region. The output ports **108a**, **108b** are separated by a distance, **d**. According to various embodiments, the
20 distance, **d**, is approximately 1 to 10 mm. It is noted, however, the other suitable distances may be incorporated and/or implemented while maintaining to the spirit and functionality of the present disclosure.

 Each wavelength of light being transmitted in a given waveguide arm **102**, **106a**, **106b** exists as an optical mode. According to various embodiments, each optical mode
25 exhibits a particular spatial extent and has a characteristic mode profile that is dependent on the waveguide parameter of the waveguide arm **102**, **106a**, **106b**. The waveguide parameter is dependent on the relative refractive indices and dimensions of the core and cladding regions and the wavelength of light being transmitted. Typically, each of the fiber-optic waveguide arms **102**, **106a**, and **106b** is single mode for wavelengths longer
30 than a certain minimum wavelength corresponding to the highest frequency of light for

which the spectrofilometer **400** is designed to work. The splitter **104** splits the light received between the two output ports **108a**, **108b**.

The spectrofilometer **400** also includes at least one dispersive optical element such as a transmission diffraction grating **204**. Additional imaging bundles, beam-shaping, collimating, and filtering optics may be included, for example, but for simplicity they are not shown here. The diffraction grating **204** interrupts the light incident on it and splits the light via the grating lines **206** and emits multiple secondary wavefronts **208**.

According to an example of use of the spectrofilometer **400**, electromagnetic radiation, **E**, such as light that is to be analyzed, is received at either or both inputs **102**, **202**. Light propagating via **102** is split by the splitter **104** between the output waveguide arms **106a**, **106b**. The split light emerges respectively from the two output ports **108a**, **108b**. The emerging light diffracts and interferes to form a characteristic interference pattern that illuminates, and can be detected by, at least one detector **110**. The detector **110** may be, for example, an array of individual photosensitive detector elements (pixels) **112**, such as a CCD detector array. Light that is received by input **202** is interrupted by the lines **206** of the diffraction grating **204**, and multiple secondary output wavefronts of light **208** emerge, respectively, from the diffraction grating **204**. The emerging light diffracts and interferes to form a characteristic diffraction interference pattern that illuminates, and can be detected by, at least one detector **110**. The overlap of the interference fringes generated using at least one splitter **104**, and the pattern generated using at least one dispersive element, such as the diffraction pattern generated by diffraction grating **204**, produces a spectroferogram that may be detected by at least one detector **110**.

Each of the output ports **108a**, **108b** has a numerical aperture which can be wavelength dependent and relates to the relative refractive indices of a waveguide core region and a waveguide cladding region, as well as the physical size of the waveguide core. Light emerging from the output ports **108a**, **108b** diffracts into the surrounding medium (typically air) with a divergence angle that depends on the numerical aperture of the respective output port **108a**, **108b**. Typically, each of the output ports **108a**, **108b** has the same numerical aperture for a given wavelength.

As the two diffracted beams emerge from the output ports **108a**, **108b**, and each propagate and diverge, the beams spatially overlap such that the fields of the wave fronts

interfere. The fields, due to the overlapping beams, provide an intensity variation that depends on a relative optical path delay difference which is, in turn, dependent on the wavelength of the emerging light. This intensity variation in a given plane is an interference fringe pattern that is characteristic of the emerging light. The delay difference
5 evolves across the detector surface **110** to form the interference fringes and is used to form an interferogram, which is a spatially or temporally dependent image or representation of the light intensity variation in the plane of the detector **110**.

Each of the outputs **208** from the diffraction grating lines **206** has a numerical aperture, which, respectively, can be wavelength dependent and relate material index
10 properties as well as the physical sizes. Light emerging from the lines **206** diffracts into the surrounding medium (typically air) with a divergence angle that depends on the numerical aperture of the respective lines. Typically, the grating lines will be uniform so each line of the lines **206** has the same numerical aperture for a given wavelength.

The one or more interferometer beam-splitting elements and/or the one or more
15 spectrometer beam-dispersing elements can be static or dynamically adjustable. As the beams diffract outward from the diffraction grating **204**, they, respectively, propagate and diverge, and the beams spatially overlap such that the fields of the wavefronts interfere. The fields, due to the overlapping beams, provide an intensity variation that depends on relative optical path delay differences which are, in turn dependent, on the wavelengths of
20 the emerging light. This intensity variation in a given plane is an interference fringe pattern that is known as a diffraction pattern that is characteristic of the emerging light. The delay difference evolves across the detector surface **210** to form the interference fringes and is used to form a diffraction pattern, which is a spatially- or temporally-dependent image or representation of the light intensity variation in the plane of the detector **110**.

Each of the elements **112** of the detector **110** is arranged, for example, to generate
25 a charge signal proportional to the intensity of light incident on the element **112**, such that the detector **110** can be used to measure the spectrofilogram. Typically, the spectrofilometer **400** is arranged such that at least two elements **112** of the detector **110** detect light from each interference fringe component of the spectrofilogram in order that
30 the spatial sampling rate is at least twice the spatial periodicity of the interference fringe pattern. This enables the spectrofilometer **400** to satisfy the Nyquist sampling criterion and

provide a lossless measurement of the fringe periodicity for the interferogram component of the spectrofilogram.

For broad band operation, the diffraction pattern generated from the dispersive element of the spectrofilometer **400** (e.g., the diffraction grating **204**) is typically arranged
5 such that, at each wavelength of light, it is confined to one or few of the elements **112** of the detector **110** to optimize the number of wavelengths that can be detected and resolved in the spectrum of incident light.

The spectrofilometer **400** includes an image pattern projection system **302** that illuminates the object of interest **304**. The object of interest **304** reflects the incident image
10 pattern from multiple points **306** and the reflection pattern **308** from the object is incident on detector **110**.

Additional collection, beam-shaping, collimating, polarizing and filtering optics may be included for example but for simplicity they are not shown here. The reflected light forms a characteristic pattern which is a spatially- and/or temporally-dependent image
15 or representation of the light intensity variation in the plane of the detector **110**. The detector **110** may be, for example, an array of individual photosensitive detector elements (pixels) **112**, such as a CCD detector array.

Each of the elements **112** of the detector **110** is arranged, for example, to generate a charge signal proportional to the intensity of light incident on the element **112**, such that
20 the detector **110** can be used to measure the reflection pattern and infer a profile.

Typically, the reflection pattern is processed by either dedicated processing electronics (not shown), or a computer programmed with suitable processing software that receives a digital representation of the interferogram. The processing electronics or computer reads the charge signals from the detector to form a spatial intensity profile, thus
25 capturing an image of the reflected pattern. The processing electronics or processing software may then process the captured spatial image data using, for example, one or more of fringe counting and weighting, transform processing, phase analysis, or any other suitable processing technique, to analyze the spatially dependent intensity pattern. This enables characterization of the light illuminating the object **304** and enables profile
30 information to be recovered that may be further analyzed and processed.

Typically, the spectrofilogram is processed by either dedicated processing electronics (not shown), or a computer programmed with suitable processing software that receives a digital representation of the spectrofilogram. The processing electronics or computer reads the charge signals from the detector to form a spatial intensity profile, thus capturing an image of the spectrofilogram. The processing electronics or processing software may then process the captured spatial image data using, for example, one or more of fringe counting and weighting, transform processing, or any other suitable processing technique to analyze the spatially dependent intensity pattern. This enables characterization of the light illuminating the spectrofilometer **400** and enables spectral and/or temporal and/or phase and/or amplitude and/or polarization information to be recovered that may be further analyzed and processed.

Through mathematically processing the spectrofilogram, it is possible to selectively choose, separate, and recombine high and low frequency components contained in the spectrofilogram. According to various embodiments, the spectrofilometer **400** includes one or more processors **405** and one or more memory **410**. The memory **410** is configured to store instructions which, when executed by the processor **405**, cause the processor **405** to process one or more signals generated by the one or more radiation sensitive elements, generate a spatial intensity profile of the incident electromagnetic radiation, and/or recover data from the spatial intensity profile. According to various embodiments, the data recovery is performed using suitable techniques such as, for example, transform processing techniques, curve fitting techniques, frequency filtering techniques, fringe counting techniques, interpolation techniques, weighting techniques, one or more orders of differentiation, one or more orders of integration, predictive analysis techniques, phase analysis techniques, machine learning techniques, artificial intelligence techniques, and/or other suitable techniques. The data includes temporal data, spectral data, phase data, amplitude data, polarization data, and/or other suitable types of data.

The spectrofilometer **400** can be used in any suitable field for any suitable application. For example, the spectrofilometer **400** may be used in the application of process monitoring, in the application of production monitoring, in manufacturing applications, in the application of in-line monitoring, in the application of closed loop, adaptive process control monitoring, and/or in other suitable applications. Furthermore, it

is noted that the spectrofilometer **400** has the advantage of simultaneously capturing and recording synchronized data sets of a multitude of data onto a single detector array. Furthermore, it is noted that the spectrofilometer **400** has the advantage of a significantly reduced data set size by capturing a multitude of data onto a single detector array and how
5 this reduces that burgeoning quantity of data associated with internet of things (IoT) applications including, but not limited to, the industrial internet of things (IIoT), process monitoring, closed-loop control, adaptive process control, and additive manufacturing applications.

The foregoing description of the embodiments should be taken as illustrating, rather
10 than as limiting the present invention as defined by the claims. As will be readily appreciated, numerous variations and combinations of the features set forth above can be utilized without departing from the present invention as set forth in the claims. Such variations are not regarded as a departure from the scope of the invention, and all such variations are intended to be included within the scope of the following claims.

15

CLAIMS

What is claimed is:

1. A spectrofilometer comprising:
at least one profilometer;
5 an enclosure; and
one or more interferometer beam-splitting elements and/or one or more spectrometer beam-dispersing elements,
wherein the one or more interferometer beam-splitting elements and/or the one or more spectrometer beam-dispersing elements:
10 are housed in the enclosure;
share one or more radiation-sensitive elements with the at least one profilometer that are arranged to generate a signal in response to incident electromagnetic radiation; and
are configured to generate one or more optical outputs arranged such that
15 respective optical axes intersect substantially in a plane of the one or more radiation-sensitive elements.
2. The spectrofilometer of claim 1, further comprising one or more reflective surfaces between the optical outputs.
20
3. The spectrofilometer of claim 2, wherein the one or more reflective surfaces comprise one or more optical coatings on one or more of the one or more reflective surfaces.
- 25 4. The spectrofilometer of claim 2, wherein the one or more reflective surfaces are microelectromechanical systems (MEMS) elements.
5. The spectrofilometer of claim 4, wherein each MEMS element is controllable and configured to reflect a portion of the incident electromagnetic radiation.
30

6. The spectrofilometer of claim 1, wherein the one or more radiation-sensitive elements are configured to detect one or more inputs originating from one or more spatially distinct locations.
- 5 7. The spectrofilometer of claim 6, wherein the one or more inputs comprise the one or more optical outputs.
8. The spectrofilometer of claim 6, wherein the one or more inputs comprise one or more imaging bundles.
- 10 9. The spectrofilometer of claim 6, wherein the one or more inputs comprise one or more optical waveguides.
10. The spectrofilometer of claim 9, wherein the one or more optical waveguides
15 comprise one or more optical fibers.
11. The spectrofilometer of claim 1, further comprising one or more optical waveguides.
- 20 12. The spectrofilometer of claim 11, wherein the one or more optical waveguides comprise one or more optical fibers.
13. The spectrofilometer of claim 12, wherein the one or more optical fibers comprise one or more of: microstructured optical fibers; and multicore optical fibers.
- 25 14. The spectrofilometer of claim 1, wherein the one or more interferometer beam-splitting elements and/or the one or more spectrometer beam-dispersing elements are dynamically adjustable.
- 30 15. The spectrofilometer of claim 1, further comprising:
one or more processors; and

a memory, configured to store instructions which, when executed by the one or more processors, cause the one or more processors to:

process one or more signals generated by the one or more radiation sensitive elements; and

5 generate a spatial intensity profile of the incident electromagnetic radiation.

16. The spectrofilometer of claim 15, wherein the instructions, when executed by the one or more processors, further cause the one or more processors to:

recover data from the spatial intensity profile using one or more of:

10 transform processing techniques;
curve fitting techniques;
frequency filtering techniques;
fringe counting techniques;
interpolation techniques;
15 weighting techniques;
one or more orders of differentiation;
one or more orders of integration;
predictive analysis techniques;
machine learning techniques; and
20 artificial intelligence techniques,

wherein the data comprises one or more of:

temporal data;
spectral data;
phase data;
25 amplitude data; and
polarization data.

17. A method of analyzing electromagnetic radiation, comprising:
providing a spectrofilometer, comprising:

30 an enclosure;
a processor;

a memory;
at least one profilometer; and
one or more interferometer beam-splitting elements and/or one or more spectrometer beam-dispersing elements,
5 wherein the one or more interferometer beam-splitting elements and/or the one or more spectrometer beam-dispersing elements:
are housed in the enclosure;
share one or more radiation sensitive elements, which are arranged to generate a signal in response to incident electromagnetic radiation; and
10 are configured to generate one or more optical outputs that are arranged such that respective optical axes intersect substantially in a plane of the one or more radiation sensitive elements; and
processing, using the processor, one or more signals generated by the one or more radiation sensitive elements to generate a spatial intensity profile of the incident
15 electromagnetic radiation.

18. The method of claim 17, further comprising:
recovering, using the processor, data from the spatial intensity profile using one or more of:
20 transform processing techniques;
curve fitting techniques;
frequency filtering techniques;
fringe counting techniques;
interpolation techniques;
25 weighting techniques;
one or more orders of differentiation;
one or more orders of integration;
predictive analysis techniques;
machine learning techniques; and
30 artificial intelligence techniques,
wherein the data comprises one or more of:

5 temporal data;
 spectral data;
 phase data;
 amplitude data; and
 polarization data.