

TITLE: PHOTONIC COHERENT DETECTION ARRAY

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CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of U.S. Provisional Patent Application No. 62/889,065 filed on August 20, 2019, which is incorporated by reference herein in its entirety.

FIELD OF THE INVENTION

[0002] The present invention relates to optical coherent detection and, in particular, relates to detection arrays for optical coherent detection.

BACKGROUND

[0003] Optical coherent detection, also known as optical heterodyne detection, is able to measure both the field amplitude and phase of an optical signal relative to a reference light signal, customarily called the local oscillator (LO), whereas direct optical detection measures only the light intensity of the optical signal. Advantages of coherent detection include near shot-noise-limited optical amplification, rejection of background light and provision of additional information through the phase.

[0004] A detection array, commonly called a focal plane array (FPA) when used at the focal plane of an imaging system, is an array of detection units that provides fast signal acquisitions of a scene by exploiting spatial parallelism. Conventional detection array technologies such as CCD and CMOS image sensors operate only in the direct optical detection mode. To achieve parallel spatial coherent detection, the direct detection array needs to be setup in an interferometric configuration, wherein free-space bulk optics is needed to coherently combine the signal light with the LO on the detection array. Such a configuration however is bulky and gives rise to the issue of the spatial-mode matching of the incoming signal beam with the LO beam that may affect the efficiency of the coherent detection.

[0005] A coherent detection array based on photonic integrated circuit (PIC) technology greatly simplifies a coherent imaging system by performing the optical interference on a photonic chip, wherein the signal light and LO light usually manifest as the same waveguide mode, so that the mode-matching issue is resolved naturally. A known form of a PIC-based coherent detection array is the Nanophotonic Coherent Imager (NCI) described by Non-Patent Document [Firooz Aflatouni, Behrooz Abiri, Angad Rekhi, and Ali Hajimiri, “Nanophotonic coherent imager,” Optics Express 23, 5117-5125 (2015)]. In the NCI, the coherent detection array is configured such that the optical antenna (grating coupler) of each detection pixel is connected individually with a waveguide to a directional coupler and photodetectors outside the sensing region. The pixel pitches of the NCI increase linearly with the number of pixels to accommodate the space for the routing waveguides, and thus the size of the resultant PIC chip increases quadratically with the number of pixels. Consequently, the described NCI scheme may be limited to a few pixels in the case where size and cost are at a premium.

[0006] Additionally, it is desirable for a coherent detection array to operate at a high frame rate for certain coherent sensing applications that benefit from real-time detection. These applications include frequency-modulated continuous-wave (FMCW) light detection and ranging (LIDAR) and optical coherence tomography (OCT). Modern high-pixel-count direct detection arrays achieve high frame rates by incorporating an analog-to-digital circuit (ADC) on every column of the pixel arrays or even at each pixel to enable parallel readouts and conversions. However, these detection arrays still have to transfer the pixel signals row-by-row to the horizontal registers of the column addressing circuit. State-of-the-art CMOS-based direct detection arrays implemented with *in situ* frame storage are able to operate at very high sampling rates, but the frame storage circuitry substantially constraints the number of pixels in the detection array. Generally, existing designs of either coherent or direct detection arrays and their operations encounter a trade-off between the pixel count and the frame rate.

BRIEF SUMMARY OF THE INVENTION

[0007] Embodiments of the present invention describe a coherent detection array implemented on a photonic integrated circuit (PIC) and multiplexing methods for readout of coherent detection signals that leverage the properties of the detection array. The coherent

detection array may comprise a plurality of coherent detection units coupling with connecting waveguides and electrical conducting paths, wherein local oscillator (LO) light is introduced into the coherent detection units through the connecting waveguides. The detection units may be configured to include free-space-to-waveguide couplers to receive incident signal light from a medium, including but not limited to free space, into the detection units, optical couplers that mix the signal light with the LO light, and photodetectors that measure the mixed signal-LO light. The electrical conducting paths may manifest as readout channels for multiplexing electrical signals, wherein the readout channels may facilitate stacking of the detection units and scalability of the coherent detection array without the need of complex waveguide routing nor optical switching. The coherent detection array also enables multiplexing methods that may leverage extra degrees of freedom of the coherent detection array. These methods may include those enabled by the local oscillator and those related to the properties and responses of the components of the PIC-based detection array. The scalable design of the coherent detection array together with multiplexing methods applicable to the array may enable the coherent detection array to achieve high pixel-count and high frame-rate operation simultaneously.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] The skilled artisan will understand that the drawings primarily are for illustrative purposes and are not intended to limit the scope of the inventive subject matter described herein. The drawings are not necessarily to scale; in some instances, various aspects of the inventive subject matter disclosed herein may be shown exaggerated or enlarged in the drawings to facilitate an understanding of different features.

[0009] FIG. 1 illustrates an example of a configuration of a coherent detection unit according to a first preferred embodiment of the present invention where two photodetectors are employed.

[0010] FIGS. 2 and 3 illustrate examples of a configuration of a coherent detection array according to a second preferred embodiment of the present invention where the embodiment of FIG. 1 is employed. FIG. 3 is a modified example of FIG. 2 where one or more electrodes of the

photodetectors of the coherent detection units may be connected by electrical conducting paths across different columns instead of across different rows.

[0011] FIGS. 4 and 5 illustrate examples of another configuration of a coherent detection unit according to a third preferred embodiment of the present invention. FIG. 4 is an embodiment where a single photodetector is employed. FIG. 5 is a modified example of FIG. 4 where one or more waveguides and/or optical couplers may be removed to simplify the detection unit.

[0012] FIGS. 6, 7, 8 and 9 illustrate examples of a configuration of a coherent detection array according to a fourth preferred embodiment of the present invention where a single photodetector at each detection unit may be employed. FIG. 6 is coherent detection array where the embodiment of FIG. 4 is employed. FIG. 7 is a first modified example of FIG. 6 where one or more electrodes of the photodetectors of the detection units may be connected by electrical conducting paths across different columns instead of across different rows. FIG. 8 is a second modified example of FIG. 6 where the embodiment of FIG. 5 is employed. FIG. 9 is a third modified example of FIG. 6 where the modifications to FIG. 6 according to both FIGS. 7 and 8 are incorporated.

[0013] FIGS. 10, 11, 12 and 13 illustrate examples of a configuration of a coherent detection unit according to a fifth preferred embodiment of the present invention where the two polarizations of the input light may be detected at the detection unit separately. FIG. 10 is an embodiment where the input light may be coupled to the detection unit through a polarized-light separating free-space-to-waveguide coupler and a single photodetector may be employed for the detection of each polarization of light. FIG. 11 is a first modified example of FIG. 10 where a single local oscillator source may be used to interfere with the two polarizations of the input light. FIG. 12 is a second modified example of FIG. 10 where one or more waveguides may be removed to simplify the coherent detection unit. FIG. 13 is a third modified example of FIG. 10 where the modifications to FIG. 10 according to both FIGS. 11 and 12 are incorporated.

[0014] FIGS. 14, 15, 16, 17, 18, 19, 20 and 21 illustrate examples of a configuration of a coherent detection array according to a sixth preferred embodiment of the present invention where the two polarizations of the input light may be detected at the detection units of the array separately. FIG. 14 is coherent detection array where the embodiment of FIG. 10 is employed. FIG. 15 is a first modified example of FIG. 14 where one or more electrodes of the photodetectors of the

detection units may be connected by electrical conducting paths across different columns instead of across different rows. FIG. 16 is a second modified example of FIG. 14 where the embodiment of FIG. 11 is employed. FIG. 17 is a third modified example of FIG. 14 where the modifications to FIG. 14 according to both FIGS. 15 and 16 are incorporated. FIG. 18 is a fourth modified example of FIG. 14 where the embodiment of FIG. 12 is employed. FIG. 19 is a fifth modified example of FIG. 14 where the modifications to FIG. 14 according to both FIGS. 15 and 18 are incorporated. FIG. 20 is a sixth modified example of FIG. 14 where the embodiment of FIG. 13 is employed. FIG. 21 is a seventh modified example of FIG. 14 where the modifications to FIG. 14 according to both FIGS. 15 and 20 are incorporated.

[0015] FIGS. 22 and 23 illustrate examples of another configuration of a coherent detection unit according to a seventh preferred embodiment of the present invention where the two polarizations of the input light may be detected at the detection unit separately. FIG. 22 is an embodiment where the input light may be coupled to the detection unit through a polarized-light separating free-space-to-waveguide coupler and two photodetectors may be employed for the detection of each polarization of light. FIG. 23 is a modified example of FIG. 22 where a single local oscillator source may be used to interfere with the two polarizations of the input light.

[0016] FIGS. 24, 25, 26 and 27 illustrate examples of another configuration of a coherent detection array according to an eighth preferred embodiment of the present invention where the two polarizations of the input light may be detected at the detection units of the array separately. FIG. 24 is coherent detection array where the embodiment of FIG. 22 is employed. FIG. 25 is a first modified example of FIG. 24 where one or more electrodes of the photodetectors of the detection units may be connected by electrical conducting paths across different columns instead of across different rows. FIG. 26 is a second modified example of FIG. 24 where the embodiment of FIG. 23 is employed. FIG. 27 is a third modified example of FIG. 24 where the modifications to FIG. 24 according to both FIGS. 25 and 26 are incorporated.

[0017] FIGS. 28 illustrates a conceptual setup of a coherent detection apparatus comprising a coherent detection array, an optical input circuit, an electrical multiplexing circuit and an electrical readout circuit.

[0018] FIGS. 29A and 29B graphically illustrate the concept of an embodiment of a multiplexing method exploiting the local oscillator for a coherent detection array of the present

invention. FIG. 29A is a graph showing an example of the frequency spectrum of the combined photocurrent or signal of connected detection units in a coherent detection array without the use of frequency offsets in the local oscillator. FIG. 29B is a graph showing an example of the frequency spectrum of the combined photocurrent or signal of connected detection units in a coherent detection array with frequency offsets applied in the local oscillator.

[0019] FIGS. 30A-C graphically illustrate the concept of an embodiment of a multiplexing method exploiting the photodetector responsivity for a coherent detection array of the present invention. FIG. 30A is a graph showing an example of the frequency spectrum of the combined photocurrent or signal of connected detection units in a coherent detection array without the use of modulation on the photodetector responsivity. FIG. 30B is a graph showing an example of the frequency spectrum of the combined photocurrent or signal of connected detection units in a coherent detection array with modulation on the photodetector responsivity. FIG. 30C is a graph showing an example of the frequency spectrum of the combined photocurrent or signal difference of connected detection units in a coherent detection array for the case of a balanced configuration with modulation on the photodetector responsivity.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0020] To achieve a coherent detection array with high pixel counts, it is desirable that the designs of the array pixel elements should allow scalability without extra complexity. In addition, existing designs of a detection array, wherein signal readout schemes exploiting time-division and space-division multiplexing are commonly used, stipulate a trade-off between pixel count and frame rate. Extra degrees of freedom to multiplex the signals may thus be desirable.

[0021] The subject technology provides an approach of a coherent detection array that enables high scalability in the number of pixels. It also enables extra degrees of freedom of the array in addition to those in the temporal and spatial domains to be used to multiplex the signal in readout. Here a pixel of the coherent detection array is generally referred to as a coherent detection unit, or simply a detection unit, of the coherent detection array.

[0022] To achieve scalability for high-pixel-count designs, the coherent detection array is configured to perform the optical interference and detection at the pixel, i.e., the coherent detection

unit. In some aspects, the coherent detection array may be implemented on a photonic chip using the PIC technology wherein each detection unit of the coherent detection array may be configured to include a waveguide to introduce the LO light into the unit, a free-space-to-waveguide coupler to couple the signal light into the PIC chip, an optical coupler to mix the LO and signal light, and on-chip photodetector(s) to measure the mixed light. The detection units may be connected by connecting waveguides and electrical conducting paths to form a coherent detection array to enable signal readout for the detection units by a multiplexing method.

[0023] For signal multiplexing, the extra degrees of freedom may be categorized into the optical and electrical domains. They may include those enabled by the local oscillator and those related to the properties and responses of the components of the PIC-based coherent detection array.

[0024] Preferred embodiments of the present invention will be described in detail below, with reference to the drawings, to illustrate the designs of coherent detection unit, coherent detection array and multiplexing methods.

Coherent Detection Unit and Coherent Focal Plane Array

First Preferred Embodiment

[0025] A coherent detection unit **100** according to the present preferred embodiment will be described with reference to FIG. 1, which illustrates a plan view of the coherent detection unit **100**. The coherent detection unit **100** illustrated in FIG. 1 is configured to include a free-space-to-waveguide coupler **11**, optical couplers **12-1** and **12-2**, waveguides **13-1**, **13-2**, **13-3**, **13-4** and **13-5**, photodetectors **14-1** and **14-2**, and electrodes **15-1**, **15-2**, **15-3** and **15-4**. The coherent detection unit **100** may also be configured to include additional components, such as one or more modulators and/or heaters, which may be used to modulate or modify the properties of the coherent detection unit. These additional components are not shown in FIG. 1. The coherent detection unit **100** may be integrated on a substrate **16** using optical waveguide technology.

[0026] The waveguide **13-1** is an optical waveguide having one end (incoming end) through which the local oscillator light $E_{LO,in}$ may be introduced, and having another end

(outgoing end) through which the local oscillator light $E_{LO,out}$ may be transmitted. The optical coupler **12-1** may split a fraction of the local oscillator light $E_{LO,in}$ from the waveguide **13-1** to the waveguide **13-2**. The waveguide **13-2** may pass the local oscillator light to the optical coupler **12-2**. Examples of the optical coupler **12-1** include, but not limited to, a Y-junction, a directional coupler, and a multi-mode interferometer.

[0027] The free-space-to-waveguide coupler **11** is a site where the signal light $E_{sig,in}$ may be coupled into the coherent detection unit **100**. The signal light $E_{sig,in}$ may be incoming in a direction perpendicular to or at an angle from the plane of the photonic chip on which the free-space-to-waveguide coupler **11** is implemented. The light received by the free-space-to-waveguide coupler **11** may flow through the waveguide **13-3** to the optical coupler **12-2**. The free-space-to-waveguide coupler **11** is generally an optical antenna that couples light from free-space or a medium into the photonic chip. Examples of a free-space-to-waveguide coupler include, but not limited to, a grating coupler commonly used in PIC designs, and novel photonic micro/nano-structures.

[0028] The optical coupler **12-2** is a coupler comprising the waveguides **13-2** and **13-3** as input ports and the waveguides **13-4** and **13-5** as output ports. The local oscillator light from the input waveguide **13-2** and the signal light from the input waveguide **13-3** may be mixed and interfere at the optical coupler **12-2**. The optical coupler **12-2** is constructed in such a manner that the light in the input waveguide **13-2** may be split between the output waveguides **13-4** and **13-5** at some fractions, and similarly the light in the input waveguide **13-3** may also be split between the output waveguides **13-4** and **13-5** at some fractions. The fractions may or may not be fixed, which also may or may not be dependent on the properties (such as, but not limited to, wavelengths) of the light input to the optical coupler, the properties and conditions (such as, but not limited to, temperature) of the optical coupler, and other unspecified factors. Examples of the optical coupler **12-2** include, but not limited to, a directional coupler and a multi-mode interferometer.

[0029] In some aspects such as a balanced configuration wherein the optical coupler **12-2** is a 50/50 coupler, the light in the input waveguide **13-2** may be split equally in magnitude between the output waveguides **13-4** and **13-5**, and the light in the input waveguide **13-3** may be split equally in magnitude between the output waveguides **13-4** and **13-5**.

[0030] The photodetector **14-1** detects the light input from the waveguide **13-4**. When the light from the waveguide **13-4** is detected by the photodetector **14-1**, a photocurrent may be generated and flow in the electrodes **15-1** and **15-2**. Similarly, the photodetector **14-2** detects the light input from the waveguide **13-5**. When the light from the waveguide **13-5** is detected by the photodetector **14-2**, a photocurrent may be generated and flow in the electrodes **15-3** and **15-4**. In some aspects, one of the electrodes **15-1** and **15-2** may represent the anode, and the other electrode may represent the cathode. Similarly, one of the electrodes **15-3** and **15-4** may represent the anode, and the other electrode may represent the cathode.

[0031] In some aspects, each of the photocurrents generated by the photodetectors **14-1** and **14-2** may include a direct component and a cross component, wherein a noise component may also be present. The direct component is proportional to the average intensities of the signal light and the local oscillator light. The cross component is proportional to the product of the electric fields of the signal light and the local oscillator light, i.e., $\langle E_{LO,in}(t)E_{Sig,in}(t) \rangle$, where t denotes time and $\langle \cdot \rangle$ denotes time averaging over a time duration that may be inversely proportional to the bandwidth of the photodetector. The noise component may be included in the direct component of the photocurrent for simplification of description.

[0032] In some aspects, the cross component may exhibit a beating of the signal light with the local oscillator light wherein the beating frequencies equal the sum or the difference of the frequencies of the signal light and the local oscillator light. The sum-beating frequency is usually very high and thus the corresponding photocurrent component may be temporally averaged out or may be suppressed due to the finite response of the photodetector. The difference-beating frequency is usually at an intermediate frequency and the corresponding photocurrent component may be temporally resolved for further processing.

[0033] In some aspects such as the case of a balanced configuration with the optical coupler **12-2** being a 50/50 coupler, by taking a difference between the photocurrents by the photodetectors **14-1** and **14-2**, the direct components of the photocurrents may be cancelled out except for a possible remnant noise component, whereas the cross components of the photocurrents may add up according to the phase difference between the cross components of the photocurrents by the photodetectors **14-1** and **14-2**.

[0034] In other aspects, the photocurrents generated by the photodetectors **14-1** and **14-2** may be modulated by modulating the responsivities of the photodetectors.

Second Preferred Embodiment

[0035] Two examples of coherent detection arrays **200** and **210** according to the present preferred embodiment will be described with reference to FIGS. **2** and **3**.

[0036] FIG. **2** illustrates a plan view of the coherent detection array **200**. The coherent detection array **200** is configured to include plural units of the coherent detection unit **100** according to the embodiment illustrated in FIG. **1**. In some aspects, the coherent detection array **200** may include other embodiments of the coherent detection units. In some aspects, the coherent detection array **200** may be constructed by concatenating plural units of the coherent detection unit **100** in a rectilinear configuration. In other aspects, embodiments of the coherent detection array may be constructed by concatenating plural units of the coherent detection unit **100** in geometries other than the rectilinear configuration. The coherent detection array **200** may be integrated on a substrate **26** using optical waveguide technology.

[0037] In some aspects of a rectilinear configuration, the coherent detection array may be configured in M rows and N columns with $M \times N$ coherent detection units, where M and N are positive integers. As an example, the embodiment of the coherent detection array **200** illustrated in FIG. **2** includes 12 coherent detection units **100-1**, **100-2**, **100-3**, **100-4**, **100-5**, **100-6**, **100-7**, **100-8**, **100-9**, **100-10**, **100-11** and **100-12** that are all coherent detection units **100** arranged in the format of 3 rows and 4 columns.

[0038] Each row of a coherent detection array **200** may be constructed by concatenating a series of the coherent detection units **100** using the waveguides **13-1** (see FIG. **1**). In some aspects, a coherent detection array according to the present preferred embodiment may be constructed in such a manner that the outgoing end of the waveguide **13-1** of a coherent detection unit **100** may be connected to the incoming end of the waveguide **13-1** of the next coherent detection unit **100**, so that the transmitted LO light $E_{LO,out}$ of a detection unit may be the incoming LO light $E_{LO,in}$ of the next connected unit. The series of the waveguides **13-1** in a row hence constitute a connecting waveguide of that row, also referred to as a row-encoding waveguide of that row to denote the role

of the waveguide. The LO light in a connecting waveguide may be coupled to the connected coherent detection units **100** through the optical couplers **12-1** (see FIGS. **1** and **2**). In such configuration, detection units on the same row of the coherent detection array may share the same local oscillator light, with each unit in the row tapping a fraction of the local oscillator light off the connecting waveguide. The fractions of the local oscillator light split off by different coherent detection units on a row may be the same or different.

[0039] A connecting waveguide may connect coherent detection units in a single row or coherent detection units in more than one row. A connecting waveguide may not need to connect all coherent detection units in a single row. A row may or may not be straight, depending on the configuration and arrangement of the coherent detection units in the coherent detection array.

[0040] Referring to FIG. **2**, the row-encoding waveguides **21-1**, **21-2**, and **21-3** each has one end through which the local oscillator light $E_{LO,in\ m}$, with $m = 1, 2, 3$ correspondingly, may be introduced, and has another end through which the local oscillator light $E_{LO,out\ m}$, with $m = 1, 2, 3$ correspondingly, may be transmitted. For a coherent detection array comprising M rows, the index m ranges from 1 to M . In FIG. **2**, the local oscillator light in the row-encoding waveguide **21-1** is coupled to the coherent detection units **100-1**, **100-2**, **100-3** and **100-4** through the optical couplers **12-1**. Similarly, the local oscillator light in the row-encoding waveguide **21-2** is coupled to the coherent detection units **100-5**, **100-6**, **100-7** and **100-8** through the optical couplers **12-1**, and the local oscillator light in the row-encoding waveguide **21-3** is coupled to the coherent detection units **100-9**, **100-10**, **100-11** and **100-12** through the optical couplers **12-1**. The optical couplers **12-1** in the coherent detection units **100-1**, **100-2**, **100-3**, **100-4**, **100-5**, **100-6**, **100-7**, **100-8**, **100-9**, **100-10**, **100-11** and **100-12** may split the same or different fractions of light into the units through appropriate designs of the optical couplers **12-1**.

[0041] The local oscillator light $E_{LO,in\ m}$ with $m = 1, 2, \dots, M$, where M is the number of rows of the coherent detection array with $M = 3$ in the illustration of FIG. **2**, may have the same or different optical frequencies, the same or different magnitudes (including zero amplitudes), and the same or different relative phases. The local oscillator light $E_{LO,in\ m}$ may also be applied at the same or different times with the same or different durations. The local oscillator light $E_{LO,in\ m}$ may be introduced into the array of the coherent detection units from the same or different light sources, which may be on-chip light sources, or external light sources off the photonic chip. These light

sources may be controlled by some optical switches and network co-located or not co-located with the coherent detection array on the photonic substrate **26**. The light sources and the optical switches and network are not shown in FIG. **2**.

[0042] In some aspects, to form a detection array with multiplexed readouts, plural rows of the coherent detection units may be concatenated in series by electrical conducting paths, also referred to as column-readout wirings, so that the coherent detection units on each column of the detection array may share the same electrical outlets that may be connected to readout circuits located at the peripheral of the coherent detection array. These electrical conducting paths may exhibit as readout channels for multiplexing. An electrical conducting path is also referred to as a wiring in the following for nomenclature simplicity.

[0043] An electrical conducting path connecting a plurality of coherent detection units may connect coherent detection units in a single column or coherent detection units in more than one column. An electrical conducting path may not need to connect all coherent detection units in a single column. A column may or may not be straight, depending on the configuration and arrangement of the coherent detection units in the coherent detection array.

[0044] In some aspects, a coherent detection array according to the present preferred embodiment illustrated in FIG. **2** may be constructed in such a manner that, for the coherent detection units in each column, the electrodes **15-1** of the photodetectors **14-1** may be connected to a column-readout wiring, the electrodes **15-3** of the photodetectors **14-2** may be connected to a column-readout wiring, and the electrodes **15-2** of the photodetectors **14-1** and the electrodes **15-4** of the photodetectors **14-2** may be connected to a common column-readout wiring. In other aspects, the electrodes **15-2** of the photodetectors **14-1** and the electrodes **15-4** of the photodetectors **14-2** may be connected to separate column-readout wirings instead of a common column-readout wiring. Electrical signals resulting from the detection units connected to the same electrical conducting path are combined (summed or differed, depending on the sign or direction of the signals) and transferred jointly to output terminals that may be connected to peripheral readout circuits. The peripheral readout circuits of the coherent detection array are not shown in FIG. **2**.

[0045] The embodiment of the coherent detection array **200** in FIG. **2** illustrates a configuration comprising 3 rows with each row including 4 coherent detection units **100**, wherein

the electrodes of the photodetectors on different rows of the 4 columns are connected by column-readout wirings. For the coherent detection units **100-1**, **100-5** and **100-9** in column 1 of the illustration in FIG. 2, the electrodes **15-1** of the photodetectors **14-1** are connected to the column-readout wiring **22-1**, the electrodes **15-3** of the photodetectors **14-2** are connected to the column-readout wiring **23-1**, and the electrodes **15-2** of the photodetectors **14-1** and the electrodes **15-4** of the photodetectors **14-2** are connected to the column-readout wiring **24-1**. The electric current at the output end of the column-readout wiring **22-1** comprises the sum of the photocurrents from the photodetectors **14-1**, the electric current at the output end of the column-readout wiring **23-1** comprises the sum of the photocurrents from the photodetectors **14-2**, and the electric current at the output end of the column-readout wiring **24-1** comprises the sum or difference of the photocurrents from the photodetectors **14-1** and **14-2**, depending on the directions of the photocurrents.

[0046] Similarly, for the coherent detection units **100-2**, **100-6** and **100-10** in column 2, the electrodes **15-1** of the photodetectors **14-1** are connected to the column-readout wiring **22-2**, the electrodes **15-3** of the photodetectors **14-2** are connected to the column-readout wiring **23-2**, and the electrodes **15-2** of the photodetectors **14-1** and the electrodes **15-4** of the photodetectors **14-2** are connected to the column-readout wiring **24-2**. The electric current at the output end of the column-readout wiring **22-2** comprises the sum of the photocurrents from the photodetectors **14-1**, the electric current at the output end of the column-readout wiring **23-2** comprises the sum of the photocurrents from the photodetectors **14-2**, and the electric current at the output end of the column-readout wiring **24-2** comprises the sum or difference of the photocurrents from the photodetectors **14-1** and **14-2**, depending on the directions of the photocurrents.

[0047] Similarly, for the coherent detection units **100-3**, **100-7** and **100-11** in column 3, the electrodes **15-1** of the photodetectors **14-1** are connected to the column-readout wiring **22-3**, the electrodes **15-3** of the photodetectors **14-2** are connected to the column-readout wiring **23-3**, and the electrodes **15-2** of the photodetectors **14-1** and the electrodes **15-4** of the photodetectors **14-2** are connected to the column-readout wiring **24-3**. The electric current at the output end of the column-readout wiring **22-3** comprises the sum of the photocurrents from the photodetectors **14-1**, the electric current at the output end of the column-readout wiring **23-3** comprises the sum of the photocurrents from the photodetectors **14-2**, and the electric current at the output end of the

column-readout wiring **24-3** comprises the sum or difference of the photocurrents from the photodetectors **14-1** and **14-2**, depending on the directions of the photocurrents.

[0048] Similarly, for the coherent detection units **100-4**, **100-8** and **100-12** in column 4, the electrodes **15-1** of the photodetectors **14-1** are connected to the column-readout wiring **22-4**, the electrodes **15-3** of the photodetectors **14-2** are connected to the column-readout wiring **23-4**, and the electrodes **15-2** of the photodetectors **14-1** and the electrodes **15-4** of the photodetectors **14-2** are connected to the column-readout wiring **24-4**. The electric current at the output end of the column-readout wiring **22-4** comprises the sum of the photocurrents from the photodetectors **14-1**, the electric current at the output end of the column-readout wiring **23-4** comprises the sum of the photocurrents from the photodetectors **14-2**, and the electric current at the output end of the column-readout wiring **24-4** comprises the sum or difference of the photocurrents from the photodetectors **14-1** and **14-2**, depending on the directions of the photocurrents.

[0049] In FIG. 2, the pads Pa are output terminals of the column-readout wirings that may be connected to peripheral readout circuits.

[0050] In FIG. 2, the coherent detection units of the coherent detection array may be viewed as being grouped by electrical conducting paths, i.e., column-readout wirings, into 4 distinct subsets (columns) wherein each coherent detection unit of the array is included in a single subset as grouped by electrical conducting paths. Alternatively, the coherent detection units of the coherent detection array may also be viewed as being grouped by connecting waveguides, i.e., row-encoding waveguides, into 3 distinct subsets (rows) wherein each coherent detection unit is included in a single subset as grouped by connecting waveguides. Each coherent detection unit of the coherent detection array may be specified by a row-encoding waveguide and a column-readout wiring.

Modified Example of Second Preferred Embodiment

[0051] FIG. 3 illustrates a plan view of the coherent detection array **210**. The coherent detection array **210** is a modified example of the coherent detection array **200** according to the embodiment illustrated in FIG. 2. Similar to the coherent detection array **200**, the coherent detection array **210** may be configured to include plural units of the coherent detection unit **100**

according to the embodiment illustrated in FIG. 1. Each row of a coherent detection array **210** may be constructed by concatenating a series of the coherent detection units **100** using the waveguides **13-1** (see FIG. 1). Plural rows of the coherent detection units **100** may be concatenated in series by electrical conducting paths to form a detection array. As an example, the embodiment of the coherent detection array **210** illustrated in FIG. 3 includes 12 coherent detection units **100-1**, **100-2**, **100-3**, **100-4**, **100-5**, **100-6**, **100-7**, **100-8**, **100-9**, **100-10**, **100-11** and **100-12** that are all coherent detection units **100** arranged in the format of 3 rows and 4 columns.

[0052] Similar to the coherent detection array **200**, the coherent detection array **210** according to the present preferred embodiment may be configured in such a manner that, for the coherent detection units in each column, either the electrodes **15-1** or the electrodes **15-2** of the photodetectors **14-1** may be connected to a column-readout wiring, and similarly either the electrodes **15-3** or the electrodes **15-4** of the photodetectors **14-2** may be connected to a column-readout wiring.

[0053] Different from the coherent detection array **200**, the coherent detection array **210** according to the present preferred embodiment may be configured in such a manner that the other electrodes of the photodetectors of the coherent detection units may be connected across different columns by electrical conducting paths, also referred to as row-encoding wirings, instead of across different rows by column-readout wirings. In some aspects, for the coherent detection units in each row of the coherent detection array **210**, either the electrodes **15-1** or the electrodes **15-2** of the photodetectors **14-1** may be connected to a row-encoding wiring, and similarly either the electrodes **15-3** or the electrodes **15-4** of the photodetectors **14-2** may be connected to a row-encoding wiring. In other aspects, the two row-encoding wirings may be combined into a common wiring instead of separate wirings. The row-encoding wirings may be exploited to multiplex the signals of the coherent detection array with a role similar to or different from that of the row-encoding waveguides of the detection array.

[0054] Referring to the coherent detection array **210** illustrated in FIG. 3. On one hand, for the coherent detection units **100-1**, **100-5** and **100-9** in column 1, the electrodes **15-1** of the photodetectors **14-1** are connected to the column-readout wiring **22-1** and the electrodes **15-3** of the photodetectors **14-2** are connected to the column-readout wiring **23-1**.

[0055] Similarly, for the coherent detection units **100-2**, **100-6** and **100-10** in column 2, the electrodes **15-1** of the photodetectors **14-1** are connected to the column-readout wiring **22-2** and the electrodes **15-3** of the photodetectors **14-2** are connected to the column-readout wiring **23-2**.

[0056] Similarly, for the coherent detection units **100-3**, **100-7** and **100-11** in column 3, the electrodes **15-1** of the photodetectors **14-1** are connected to the column-readout wiring **22-3** and the electrodes **15-3** of the photodetectors **14-2** are connected to the column-readout wiring **23-3**.

[0057] Similarly, for the coherent detection units **100-4**, **100-8** and **100-12** in column 4, the electrodes **15-1** of the photodetectors **14-1** are connected to the column-readout wiring **22-4** and the electrodes **15-3** of the photodetectors **14-2** are connected to the column-readout wiring **23-4**.

[0058] On the other hand, for the coherent detection units **100-1**, **100-2**, **100-3** and **100-4** in row 1 of the coherent detection array **210**, the electrodes **15-2** of the photodetectors **14-1** are connected to the row-encoding wiring **27-1** and the electrodes **15-4** of the photodetectors **14-2** are connected to the row-encoding wiring **28-1**.

[0059] Similarly, for the coherent detection units **100-5**, **100-6**, **100-7** and **100-8** in row 2, the electrodes **15-2** of the photodetectors **14-1** are connected to the row-encoding wiring **27-2** and the electrodes **15-4** of the photodetectors **14-2** are connected to the row-encoding wiring **28-2**.

[0060] Similarly, for the coherent detection units **100-9**, **100-10**, **100-11** and **100-12** in row 3, the electrodes **15-2** of the photodetectors **14-1** are connected to the row-encoding wiring **27-3** and the electrodes **15-4** of the photodetectors **14-2** are connected to the row-encoding wiring **28-3**.

[0061] The pads **Pa** in FIG. **3** are terminals of the column-readout wirings and the row-encoding wirings that may be connected to peripheral electrical circuits

[0062] In FIG. **3**, the coherent detection units of the coherent detection array may be viewed as being grouped by some electrical conducting paths, i.e., column-readout wirings, into 4 distinct subsets (columns) and by other electrical conducting paths, i.e., row-encoding wirings,

into 3 distinct subsets (rows), wherein each coherent detection unit of the array is included in two subsets (1 column and 1 row) as grouped by the electrical conducting paths. Each coherent detection unit of the coherent detection array may be specified by a row-encoding wiring and a column readout wiring. Alternatively, the coherent detection units of the coherent detection array may also be viewed as being grouped by connecting waveguides, i.e., row-encoding waveguides, into 3 distinct subsets (rows) wherein each coherent detection unit is included in a single subset as grouped by the connecting waveguides. Each coherent detection unit of the coherent detection array may be specified by a row-encoding waveguide and a column readout wiring.

Third Preferred Embodiment

[0063] Two examples of coherent detection units **300** and **310** according to the present preferred embodiment will be described with reference to FIGS. **4** and **5**.

[0064] FIG. **4** illustrates a plan view of the coherent detection unit **300**. The coherent detection unit **300** illustrated in FIG. **4** is configured to include a free-space-to-waveguide coupler **31**, optical couplers **32-1** and **32-2**, waveguides **33-1**, **33-2**, **33-3** and **33-4**, a photodetector **34**, and electrodes **35-1** and **35-2**. The coherent detection unit **300** may also be configured to include additional components, such as one or more modulators and/or heaters, which may be used to modulate or modify the properties of the coherent detection unit. These additional components are not shown in FIG. **4**. The coherent detection unit **300** may be integrated on a substrate **36** using optical waveguide technology.

[0065] The coherent detection unit **300** is a modified version of the coherent detection unit **100** illustrated in FIG. **1**. The coherent detection unit **300** may be understood with reference to the coherent detection unit **100** according to the embodiment illustrated in FIG. **1**, in conjunction with the following descriptions.

[0066] An essential difference between the two embodiments of the coherent detection unit illustrated in FIG. **1** and FIG. **4** is the use of one photodetector **34** in the coherent detection unit **300** instead of two photodetectors **14-1** and **14-2** in the coherent detection unit **100**. In addition, the optical coupler **32-2** in the coherent detection unit **300** is a coupler comprising the waveguides **33-2** and **33-3** as input ports and the waveguide **33-4** as an output port. The optical coupler **32-2**

may be realized by a 2×2 directional coupler with a free output port appropriately terminated, a Y-junction, or any other form that mixes light with at least two inputs ports and one output port.

[0067] In some aspects, the photocurrent generated by the photodetector **34** may include a direct component that is slowly varying in time and a cross component that is rapidly varying in time, wherein a noise component may also be present. With only one photodetector used in the coherent detection unit **300**, the photocurrent generated by the photodetector **34** may need to be filtered by an appropriate filter to suppress the direct component of the photocurrent. The filter may be installed at the detection unit or not at the detection unit. The filter is not shown in FIG. 4.

Modified Example of Third Preferred Embodiment

[0068] FIG. 5 illustrates a plan view of the coherent detection unit **310**. The coherent detection unit **310** illustrated in FIG. 5 is a modified example of the coherent detection unit **300** according to the embodiment illustrated in FIG. 4.

[0069] The coherent detection unit **310** illustrated in FIG. 5 is similar to the coherent detection unit **300** illustrated in FIG. 4 with an essential difference of the removal of the waveguide **33-2** and the combining of the optical couplers **32-1** and **32-2** into a single optical coupler **32-3** for simplification. The optical coupler **32-3** of the coherent detection **310** in FIG. 5 plays the roles of both the optical couplers **32-1** and **32-2** of the coherent detection unit **300** in FIG. 4. For the coherent detection unit **310**, the optical coupler **32-3** may directly mix the local oscillator light in the waveguide **33-1** with the signal light in the waveguide **33-3**. The mixed light may be transferred to the waveguide **33-4** and the outgoing segment of the waveguide **33-1**.

[0070] In some aspects, the optical coupler **32-3** of the coherent detection unit **310** may be constructed in such a manner that it may transfer a majority fraction of the signal light from the waveguide **33-3** to the waveguide **33-4**, and transfer a minority fraction of the signal light from the waveguide **33-3** to the outgoing segment of the waveguide **33-1**. An example of the light splitting ratio of the optical coupler **32-3** is 999:1.

Fourth Preferred Embodiment

[0071] Four examples of coherent detection arrays **400**, **410**, **420** and **430** according to the present preferred embodiment will be described with reference to FIGS. **6**, **7**, **8**, and **9**.

[0072] FIG. **6** illustrates a plan view of the coherent detection array **400**. The coherent detection array **400** is configured to include plural units of the coherent detection unit **300** according to the embodiment illustrated in FIG. **4**. In some aspects, the coherent detection array **400** may include other embodiments of the coherent detection units. In some aspects, the coherent detection array **400** may be constructed by concatenating plural units of the coherent detection unit **300** in a rectilinear configuration. In other aspects, embodiments of the coherent detection array may be constructed by concatenating plural units of the coherent detection unit **300** in geometries other than the rectilinear configuration. The coherent detection array **400** may be integrated on a substrate **46** using optical waveguide technology.

[0073] The coherent detection array **400** illustrated in FIG. **6** is similar to the coherent detection array **200** illustrated in FIG. **2** with an essential difference of employing the coherent detection unit **300** according to the embodiment illustrated in FIG. **4** as a building block of the detection array, instead of the coherent detection unit **100** used in the coherent detection array **200**. In some aspects of a rectilinear configuration, the coherent detection array may be configured in M rows and N columns with $M \times N$ coherent detection units. As an example, the embodiment of the coherent detection array **400** illustrated in FIG. **6** includes 12 coherent detection units **300-1**, **300-2**, **300-3**, **300-4**, **300-5**, **300-6**, **300-7**, **300-8**, **300-9**, **300-10**, **300-11** and **300-12** that are all coherent detection units **300** arranged in the format of 3 rows and 4 columns.

[0074] The coherent detection array **400** may be understood with reference to the coherent detection array **200** according to the embodiment illustrated in FIG. **2**, in conjunction with the following descriptions.

[0075] Each row of a coherent detection array **400** may be constructed by concatenating a series of the coherent detection units **300** using the waveguides **33-1** (see FIG. **4**). In some aspects, a coherent detection array according to the present preferred embodiment may be constructed in such a manner that the outgoing end of the waveguide **33-1** of a coherent detection unit **300** may be connected to the incoming end of the waveguide **33-1** of the next coherent detection unit **300**, so that the transmitted LO light $E_{LO,out}$ of a detection unit may be the incoming LO light $E_{LO,in}$ of the next connected unit. The series of the waveguides **33-1** in a row constitute a connecting

waveguide of that row, also referred to as a row-encoding waveguide of that row. The LO light in a connecting waveguide may be coupled to the connected coherent detection units **300** through the optical couplers **32-1** (see FIGS. **4** and **6**).

[0076] For the coherent detection array **400** illustrated in FIG. **6**, the row-encoding waveguides are the waveguides **41-1**, **41-2** and **41-3**. The LO light in the row-encoding waveguide **41-1** is coupled to the coherent detection units **300-1**, **300-2**, **300-3** and **300-4** through the optical couplers **32-1**. Similarly, the LO light in the row-encoding waveguide **41-2** is coupled to the coherent detection units **300-5**, **300-6**, **300-7** and **300-8** through the optical couplers **32-1**, and the LO light in the row-encoding waveguide **41-3** is coupled to the coherent detection units **300-9**, **300-10**, **300-11** and **300-12** through the optical couplers **32-1**. The optical couplers **32-1** in the coherent detection units **300-1**, **300-2**, **300-3**, **300-4**, **300-5**, **300-6**, **300-7**, **300-8**, **300-9**, **300-10**, **300-11** and **300-12** may split the same or different fractions of light into the units through appropriate designs of the optical couplers **32-1**.

[0077] Plural rows of the coherent detection units may be concatenated in series by electrical conducting paths, also referred to as column-readout wirings. The coherent detection units connected by each column-readout wiring may share the same electrical outlets that may be connected to readout circuits located at the peripheral of the coherent detection array. In some aspects, a coherent detection array according to the present preferred embodiment may be constructed in such a manner that, for the coherent detection units in each column, the electrodes **35-1** of the photodetectors **34** may be connected to a column-readout wiring, and similarly the electrodes **35-2** of the photodetectors **34** may be connected to a column-readout wiring.

[0078] For the coherent detection units **300-1**, **300-5** and **300-9** in column 1 of the illustration in FIG. **6**, the electrodes **35-1** of the photodetectors **34** are connected to the column-readout wiring **42-1** and the electrodes **35-2** of the photodetectors **34** are connected to the column-readout wiring **43-1**. Similarly, for the coherent detection units **300-2**, **300-6** and **300-10** in column 2, the electrodes **35-1** of the photodetectors **34** are connected to the column-readout wiring **42-2** and the electrodes **35-2** of the photodetectors **34** are connected to the column-readout wiring **43-2**. Similarly, for the coherent detection units **300-3**, **300-7** and **300-11** in column 3, the electrodes **35-1** of the photodetectors **34** are connected to the column-readout wiring **42-3** and the electrodes **35-2** of the photodetectors **34** are connected to the column-readout wiring **43-3**. Similarly, for the

coherent detection units **300-4**, **300-8** and **300-12** in column 4, the electrodes **35-1** of the photodetectors **34** are connected to the column-readout wiring **42-4** and the electrodes **35-2** of the photodetectors **34** are connected to the column-readout wiring **43-4**.

[0079] Similar to FIG. 2, the pads Pa in FIG. 6 are output terminals of the column-readout wirings that may be connected to peripheral readout circuits.

First Modified Example of Fourth Preferred Embodiment

[0080] FIG. 7 illustrates a plan view of the coherent detection array **410**. The coherent detection array **410** is a modified example of the coherent detection array **400** according to the embodiment illustrated in FIG. 6. Similar to the coherent detection array **400**, the coherent detection array **410** may be configured to include plural units of the coherent detection unit **300** according to the embodiment illustrated in FIG. 4. Each row of a coherent detection array **410** may be constructed by concatenating a series of the coherent detection units **300** using the waveguides **33-1** (see FIG. 4). Plural rows of the coherent detection units **300** may be concatenated in series by electrical conducting paths to form a detection array. As an example, the embodiment of the coherent detection array **410** illustrated in FIG. 7 includes 12 coherent detection units **300-1**, **300-2**, **300-3**, **300-4**, **300-5**, **300-6**, **300-7**, **300-8**, **300-9**, **300-10**, **300-11** and **300-12** that are all coherent detection units **300** arranged in the format of 3 rows and 4 columns.

[0081] Similar to the coherent detection array **400**, the coherent detection array **410** according to the present preferred embodiment may be configured in such a manner that, for the coherent detection units in each column, either the electrodes **35-1** or the electrodes **35-2** of the photodetectors **34** may be connected to a column-readout wiring.

[0082] Different from the coherent detection array **400**, the coherent detection array **410** according to the present preferred embodiment may be configured in such a manner that the other electrodes of the photodetectors of the coherent detection units may be connected across different columns by electrical conducting paths, also referred to as row-encoding wirings, instead of across different rows by column-readout wirings. For the coherent detection units **300** in each row of the coherent detection array **410**, either the electrodes **35-1** or the electrodes **35-2** of the photodetectors **34** may be connected to a row-encoding wiring.

[0083] Referring to the coherent detection array **410** illustrated in FIG. 7. On one hand, the electrodes **35-2** of the photodetectors **34** of the coherent detection units **300-1**, **300-5** and **300-9** in column 1 are connected to the column-readout wiring **43-1**. Similarly, the electrodes **35-2** of the photodetectors **34** of the coherent detection units **300-2**, **300-6** and **300-10** in column 2 are connected to the column-readout wiring **43-2**, the electrodes **35-2** of the photodetectors **34** of the coherent detection units **300-3**, **300-7** and **300-11** in column 3 are connected to the column-readout wiring **43-3**, and the electrodes **35-2** of the photodetectors **34** of the coherent detection units **300-4**, **300-8** and **300-12** in column 4 are connected to the column-readout wiring **43-4**.

[0084] On the other hand, the electrodes **35-1** of the photodetectors **34** of the coherent detection units **300-1**, **300-2**, **300-3** and **300-4** in row 1 are connected to the row-encoding wiring **44-1**. Similarly, the electrodes **35-1** of the photodetectors **34** of the coherent detection units **300-5**, **300-6**, **300-7** and **300-8** in row 2 are connected to the row-encoding wiring **44-2**, and the electrodes **35-1** of the photodetectors **34** of the coherent detection units **300-9**, **300-10**, **300-11** and **300-12** in row 3 are connected to the row-encoding wiring **44-3**.

[0085] The pads **Pa** in FIG. 7 are terminals of the column-readout wirings and the row-encoding wirings that may be connected to peripheral electrical circuits

Second Modified Example of Fourth Preferred Embodiment

[0086] FIG. 8 illustrates a plan view of the coherent detection array **420**. The coherent detection array **420** is another modified example of the coherent detection array **400** according to the embodiment illustrated in FIG. 6.

[0087] The coherent detection array **420** illustrated in FIG. 8 is similar to the coherent detection array **400** illustrated in FIG. 6 with an essential difference of employing the coherent detection unit **310** according to the embodiment illustrated in FIG. 5 as a building block of the detection array, instead of the coherent detection unit **300** used in the coherent detection array **400**. In some aspects of a rectilinear configuration, the coherent detection array may be configured in M rows and N columns with $M \times N$ coherent detection units. As an example, the embodiment of the coherent detection array **420** illustrated in FIG. 8 includes 12 coherent detection units **310-1**,

310-2, 310-3, 310-4, 310-5, 310-6, 310-7, 310-8, 310-9, 310-10, 310-11 and 310-12 that are all coherent detection units **310** arranged in the format of 3 rows and 4 columns.

Third Modified Example of Fourth Preferred Embodiment

[0088] FIG. 9 illustrates a plan view of the coherent detection array **430**. The coherent detection array **430** is another modified example of the coherent detection array **400** according to the embodiment illustrated in FIG. 6.

[0089] The coherent detection array **430** combines the modifications made to the coherent detection array **400** according to the coherent detection array **410** in FIG. 7 and the coherent detection array **420** in FIG. 8. The coherent detection array **430** may be understood with reference to the coherent detection arrays **410** and **420** according to the embodiments illustrated in FIGS. 7 and 8, in conjunction with the following descriptions.

[0090] On one hand, similar to the coherent detection array **420**, the coherent detection array **430** employs the coherent detection unit **310** according to the embodiment illustrated in FIG. 5 as a building block of the detection array, instead of the coherent detection unit **300** used in the coherent detection arrays **400** and **410**. On the other hand, similar to the coherent detection array **410**, the coherent detection array **430** may be configured in such a manner that either the electrodes **35-1** or the electrodes **35-2** of the photodetectors **34** of the coherent detection units **310** in each column of the detection array may be connected to a column-readout wiring across the rows of that column, while the other electrodes of the photodetectors **34** of the coherent detection units **310** in each row of the detection array may be connected to a row-encoding wiring across the columns of that row.

[0091] Referring to the coherent detection array **430** illustrated in FIG. 9. On one hand, the electrodes **35-2** of the photodetectors **34** of the coherent detection units **310-1, 310-5 and 310-9** in column 1 are connected to the column-readout wiring **43-1**. Similarly, the electrodes **35-2** of the photodetectors **34** of the coherent detection units **310-2, 310-6 and 310-10** in column 2 are connected to the column-readout wiring **43-2**, the electrodes **35-2** of the photodetectors **34** of the coherent detection units **310-3, 310-7 and 310-11** in column 3 are connected to the column-readout

wiring **43-3**, and the electrodes **35-2** of the photodetectors **34** of the coherent detection units **310-4**, **310-8** and **310-12** in column 4 are connected to the column-readout wiring **43-4**.

[0092] On the other hand, the electrodes **35-1** of the photodetectors **34** of the coherent detection units **310-1**, **310-2**, **310-3** and **310-4** in row 1 are connected to the row-encoding wiring **44-1**. Similarly, the electrodes **35-1** of the photodetectors **34** of the coherent detection units **310-5**, **310-6**, **310-7** and **310-8** in row 2 are connected to the row-encoding wiring **44-2**, and the electrodes **35-1** of the photodetectors **34** of the coherent detection units **310-9**, **310-10**, **310-11** and **310-12** in row 3 are connected to the row-encoding wiring **44-3**.

Fifth Preferred Embodiment

[0093] Four examples of coherent detection units **500**, **510**, **520** and **530** according to the present preferred embodiment will be described with reference to FIGS. **10**, **11**, **12**, and **13**.

[0094] FIG. **10** illustrates a plan view of the coherent detection unit **500**. The coherent detection unit **500** illustrated in FIG. **10** is configured to include a polarized-light separating free-space-to-waveguide coupler **51**, optical couplers **52-1**, **52-2**, **52-3** and **52-4**, waveguides **53-1**, **53-2**, **53-3**, **53-4**, **53-5**, **53-6**, **53-7** and **53-8**, photodetectors **54-1** and **54-2**, and electrodes **55-1**, **55-2**, **55-3** and **55-4**. The coherent detection unit **500** may also be configured to include additional components, such as one or more modulators and/or heaters, which may be used to modulate or modify the properties of the coherent detection unit. These additional components are not shown in FIG. **10**. The coherent detection unit **500** may be integrated on a substrate **56** using optical waveguide technology.

[0095] The coherent detection unit **500** is a modified version of the coherent detection unit **300** illustrated in FIG. **4**. The coherent detection unit **500** is configured to detect incoming signal light, which may be multiplexed with polarizations in the x and y directions, wherein the x and y directions are an example of an orthogonal basis of light polarization defined by the design of the polarized-light separating free-space-to-waveguide coupler **51**, in such a way that the two polarization components may be measured separately. The coherent detection unit **500** may be understood with reference to the coherent detection unit **300** according to the embodiment illustrated in FIG. **4**, in conjunction with the following descriptions.

[0096] The coherent detection unit **500** is constructed by combining coherent detection sub-units **301** and **302** (see FIG. 10), each of which is similar to the coherent detection unit **300**, with a polarized-light separating free-space-to-waveguide coupler **51** replacing the free-space-to-waveguide coupler **31** of the coherent detection unit **300**. The coherent detection sub-unit **301** is configured to include the polarized-light separating free-space-to-waveguide coupler **51**, the optical couplers **52-1** and **52-2**, the waveguides **53-1**, **53-2**, **53-3** and **53-4**, the photodetector **54-1**, and the electrodes **55-1** and **55-2**. The coherent detection sub-unit **302** is configured to include the same polarized-light separating free-space-to-waveguide coupler **51**, the optical couplers **52-3** and **52-4**, the waveguides **53-5**, **53-6**, **53-7** and **53-8**, the photodetector **54-2**, and the electrodes **55-3** and **55-4**. In such configuration, the polarized-light separating free-space-to-waveguide coupler **51** is a common component of the two coherent detection sub-units **301** and **302**.

[0097] In FIG. 10, the waveguide **53-1** has one end through which the local oscillator light $E_{LO,in\ x}$ may be introduced and the other end through which the local oscillator light $E_{LO,out\ x}$ may be transmitted, and the waveguide **53-5** has one end through which the local oscillator light $E_{LO,in\ y}$ may be introduced and the other end through which the local oscillator light $E_{LO,out\ y}$ may be transmitted. In some aspects, $E_{LO,in\ x}$ and $E_{LO,in\ y}$ (and correspondingly $E_{LO,out\ x}$ and $E_{LO,out\ y}$) may manifest in the waveguides **53-1** and **53-5** as the same waveguide mode, i.e., the fundamental TE mode as commonly considered in photonics integrated circuits for optimal propagation and coupling efficiencies. In other aspects, $E_{LO,in\ x}$ may be the same as or different from $E_{LO,in\ y}$ in terms of properties such as amplitude, frequency and phase.

[0098] The coherent detection unit **500** uses the polarized-light separating free-space-to-waveguide coupler **51** to receive the signal light $E_{Sig,in}$ that may comprise multiplexed x-polarized light and y-polarized light. The signal light $E_{Sig,in}$ may be received and separated into x-polarized light and y-polarized light by the polarized-light separating free-space-to-waveguide coupler **51**. On one hand, the x-polarized light may be carried into the coherent detection sub-unit **301** through the waveguide **53-3** and may result in a photocurrent in the electrodes **55-1** and **55-2** when detected by the photodetector **54-1**. On the other hand, the y-polarized light may be carried into the coherent detection sub-unit **302** through the waveguide **53-7** and may result in a photocurrent in the electrodes **55-3** and **55-4** when detected by the photodetector **54-2**.

[0099] In some aspects, the photocurrent generated by each of the photodetectors **54-1** and **54-2** may include a direct component that is slowly varying in time and a cross component that is rapidly varying in time, wherein a noise component may also be present. With one photodetector per polarization used in the coherent detection unit **500**, the photocurrents generated by the photodetectors **54-1** and **54-2** may need to be filtered by appropriate filters to suppress the direct components of the photocurrents. The filters may be installed at the detection unit or not at the detection unit. The filters are not shown in FIG. **10**.

First Modified Example of Fifth Preferred Embodiment

[0100] FIG. **11** illustrates a plan view of the coherent detection unit **510**. The coherent detection unit **510** illustrated in FIG. **11** is a modified example of the coherent detection unit **500** according to the embodiment illustrated in FIG. **10**.

[0101] The coherent detection unit **510** in FIG. **11** is similar to the coherent detection unit **500** in FIG. **10** with an essential difference of moving the optical coupler **52-3** to the waveguide **53-1** to couple the same local oscillator light from the waveguide **53-1** to the waveguide **53-6** as the local oscillator light to the waveguide **53-2**. In this way, the x-polarized and y-polarized components of the signal light coupled into the detection unit **510** may be mixed with the same local oscillator light $E_{LO,in}$. The waveguide **53-5** may be removed accordingly.

Second Modified Example of Fifth Preferred Embodiment

[0102] FIG. **12** illustrates a plan view of the coherent detection unit **520**. The coherent detection unit **520** illustrated in FIG. **12** is another modified example of the coherent detection unit **500** according to the embodiment illustrated in FIG. **10**.

[0103] The coherent detection unit **520** illustrated in FIG. **12** is similar to the coherent detection unit **500** illustrated in FIG. **10** wherein the coherent detection unit **520** is constructed by combining coherent detection sub-units **311** and **312**, which are similar to the coherent detection sub-units **301** and **302** in FIG. **10** with essential differences of the removals of the waveguides **53-2** and **53-6**, and the combining of the optical couplers **52-1** and **52-2** into an optical coupler **52-5**

and the combining of the optical couplers **52-3** and **52-4** into an optical coupler **52-6** for simplification.

[0104] The optical coupler **52-5** of the coherent detection unit **520** in FIG. **12** plays the roles of both the optical couplers **52-1** and **52-2** of the coherent detection unit **500** in FIG. **10**, and similarly the optical coupler **52-6** of the coherent detection unit **520** plays the roles of both the optical couplers **52-3** and **52-4** of the coherent detection unit **500**. For the coherent detection unit **520**, the optical coupler **52-5** may directly mix the local oscillator light in the waveguide **53-1** with the signal light in the waveguide **53-3**. The mixed light may be transferred to the waveguide **53-4** and the outgoing segment of the waveguide **53-1**. Similarly, the optical coupler **52-6** may directly mix the local oscillator light in the waveguide **53-5** with the signal light in the waveguide **53-7**. The mixed light may be transferred to the waveguide **53-8** and the outgoing segment of the waveguide **53-5**.

[0105] In some aspects, the optical coupler **52-5** of the coherent detection unit **520** may be constructed in such a manner that it may transfer a majority fraction of the signal light from the waveguide **53-3** to the waveguide **53-4**, and transfer a minority fraction of the signal light from the waveguide **53-3** to the outgoing segment of the waveguide **53-1**. Similarly, the optical coupler **52-6** of the coherent detection unit **520** may be constructed in such a manner that it may transfer a majority fraction of the signal light from the waveguide **53-7** to the waveguide **53-8**, and transfer a minority fraction of the signal light from the waveguide **53-7** to the outgoing segment of the waveguide **53-5**. An example of the light splitting ratio for the optical couplers **52-5** and **52-6** is 999:1.

Third Modified Example of Fifth Preferred Embodiment

[0106] FIG. **13** illustrates a plan view of the coherent detection unit **530**. The coherent detection unit **530** illustrated in FIG. **13** is another modified example of the coherent detection unit **500** according to the embodiment illustrated in FIG. **10**.

[0107] The coherent detection unit **530** combines the modifications made to the coherent detection unit **500** according to the coherent detection unit **510** in FIG. **11** and the coherent detection unit **520** in FIG. **12**. The coherent detection unit **530** may be understood with reference

to the coherent detection units **510** and **520** according to the embodiments illustrated in FIGS. **11** and **12**, in conjunction with the following descriptions.

[0108] On one hand, similar to the coherent detection unit **520**, the coherent detection unit **530** has the optical couplers **52-1** and **52-2** combined into a single optical coupler **52-5** and the waveguide **53-2** removed from the coherent detection unit **500** (see FIG. **10**) for simplification. On the other hand, similar to the coherent detection unit **510**, the coherent detection unit **530** has the optical coupler **52-3** moved to the waveguide **53-1** to couple the same local oscillator light from the waveguide **53-1** to the waveguide **53-6** as the local oscillator light to the waveguide **53-4**. In this way, the x-polarized and y-polarized components of the signal light coupled into the detection unit **530** may be mixed with the same local oscillator light $E_{LO,in}$. The waveguide **53-5** may be removed accordingly.

Sixth Preferred Embodiment

[0109] Eight examples of coherent detection arrays **600**, **610**, **620**, **630**, **640**, **650**, **660** and **670** according to the present preferred embodiment will be described with reference to FIGS. **14**, **15**, **16**, **17**, **18**, **19**, **20** and **21**.

[0110] FIG. **14** illustrates a plan view of the coherent detection array **600**. The coherent detection array **600** is configured to include plural units of the coherent detection unit **500** according to the embodiment illustrated in FIG. **10**. In some aspects, the coherent detection array **600** may include other embodiments of the coherent detection units. In some aspects, the coherent detection array **600** may be constructed by concatenating plural units of the coherent detection unit **500** in a rectilinear configuration. In other aspects, embodiments of the coherent detection array may be constructed by concatenating plural units of the coherent detection unit **500** in geometries other than the rectilinear configuration. The coherent detection array **600** may be integrated on a substrate **66** using optical waveguide technology.

[0111] The coherent detection array **600** illustrated in FIG. **14** is similar to the coherent detection array **200** illustrated in FIG. **2** with an essential difference of employing the coherent detection unit **500** according to the embodiment illustrated in FIG. **10** as a building block of the detection array, instead of the coherent detection unit **100** used in the coherent detection array **200**.

In some aspects of a rectilinear configuration, the coherent detection array may be configured in M rows and N columns with $M \times N$ coherent detection units. As an example, the embodiment of the coherent detection array **600** illustrated in FIG. **14** includes 12 coherent detection units **500-1**, **500-2**, **500-3**, **500-4**, **500-5**, **500-6**, **500-7**, **500-8**, **500-9**, **500-10**, **500-11** and **500-12** that are all coherent detection units **500** arranged in the format of 3 rows and 4 columns.

[0112] The coherent detection array **600** may be understood with reference to the coherent detection array **200** according to the embodiment illustrated in FIG. **2**, in conjunction with the following descriptions.

[0113] In some aspects with the coherent detection units **500** configured to detect incoming signal light that may be multiplexed with polarizations in the x and y directions, each row of a coherent detection array **600** may be configured to comprise a row-encoding waveguide for the x -polarized light and a row-encoding waveguide for the y -polarized light, with separate LO light introduced to each row-encoding waveguide. The series of the waveguides **53-1** and **53-5** in a row of connected coherent detection units **500** in the coherent detection array **600** constitute row-encoding waveguides of that row (see FIGS. **10** and **14**). The LO light in the row-encoding waveguide for the x polarization may be coupled to the connected coherent detection units **500** through the optical couplers **52-1**, and the LO light in the row-encoding waveguide for the y polarization may be coupled to the connected coherent detection units **500** through the optical couplers **52-3** (see FIGS. **10** and **14**).

[0114] The electric fields of the LO light introduced to the row-encoding waveguides of the coherent detection array are $E_{LO,in\ m\ x}$ and $E_{LO,in\ m\ y}$ with $m = 1, 2, \dots, M$, where M is the number of rows of the detection array. The corresponding transmitted LO fields out of the waveguides are $E_{LO,out\ mx}$ and $E_{LO,out\ my}$. The LO fields $E_{LO,in\ m\ x}$ and $E_{LO,in\ m\ y}$ for different m may have the same or different optical frequencies, the same or different magnitudes, and the same or different relative phases.

[0115] For the coherent detection array **600** illustrated in FIG. **14**, the LO fields $E_{LO,in1x}$ and $E_{LO,in1y}$ are introduced respectively to the row-encoding waveguides **61-1** and **61-2** in row 1, the LO fields $E_{LO,in2x}$ and $E_{LO,in2y}$ are introduced respectively to the row-encoding waveguides

61-3 and **61-4** in row 2, and the LO fields $E_{LO,in3x}$ and $E_{LO,in3y}$ are introduced respectively to the row-encoding waveguides **61-5** and **61-6** in row 3.

[0116] In some aspects, a coherent detection array according to the present preferred embodiment may be constructed in such a manner that, for the coherent detection units in each column, the electrodes **55-1** and **55-2** of the photodetectors **54-1**, and the electrodes **55-3** and **55-4** of the photodetectors **54-2** may be connected to separate column-readout wirings. In other aspects, either the electrodes **55-1** or the electrodes **55-2** of the photodetectors **54-1** and either the electrodes **55-3** or the electrodes **55-4** of the photodetectors **54-2** may be connected to a common column-readout wiring instead of separate column-readout wirings.

[0117] For the coherent detection units **500-1**, **500-5** and **500-9** in column 1 of the illustration in FIG. 14, the electrodes **55-1** and **55-2** of the photodetectors **54-1** are connected to the column-readout wirings **62-1** and **63-1** respectively, and the electrodes **55-3** and **55-4** of the photodetectors **54-2** are connected to the column-readout wirings **64-1** and **65-1** respectively. Similarly, for the coherent detection units **500-2**, **500-6** and **500-10** in column 2, the electrodes **55-1** and **55-2** of the photodetectors **54-1** are connected to the column-readout wirings **62-2** and **63-2** respectively, and the electrodes **55-3** and **55-4** of the photodetectors **54-2** are connected to the column-readout wirings **64-2** and **65-2** respectively. Similarly, for the coherent detection units **500-3**, **500-7** and **500-11** in column 3, the electrodes **55-1** and **55-2** of the photodetectors **54-1** are connected to the column-readout wirings **62-3** and **63-3** respectively, and the electrodes **55-3** and **55-4** of the photodetectors **54-2** are connected to the column-readout wirings **64-3** and **65-3** respectively. Similarly, for the coherent detection units **500-4**, **500-8** and **500-12** in column 4, the electrodes **55-1** and **55-2** of the photodetectors **54-1** are connected to the column-readout wirings **62-4** and **63-4** respectively, and the electrodes **55-3** and **55-4** of the photodetectors **54-2** are connected to the column-readout wirings **64-4** and **65-4** respectively.

[0118] Similar to FIG. 2, the pads Pa in FIG. 14 are output terminals of the column-readout wirings that may be connected to peripheral readout circuits.

First Modified Example of Sixth Preferred Embodiment

[0119] FIG. 15 illustrates a plan view of the coherent detection array 610. The coherent detection array 610 is a modified example of the coherent detection array 600 according to the embodiment illustrated in FIG. 14. Similar to the coherent detection array 600, the coherent detection array 610 may be configured to include plural units of the coherent detection unit 500 according to the embodiment illustrated in FIG. 10. Each row of a coherent detection array 610 may be constructed by concatenating a series of the coherent detection units 500 using the waveguides 53-1 (see FIG. 10). Plural rows of the coherent detection units 500 may be concatenated in series by electrical conducting paths to form a detection array. As an example, the embodiment of the coherent detection array 610 illustrated in FIG. 15 includes 12 coherent detection units 500-1, 500-2, 500-3, 500-4, 500-5, 500-6, 500-7, 500-8, 500-9, 500-10, 500-11 and 500-12 that are all coherent detection units 500 arranged in the format of 3 rows and 4 columns.

[0120] Similar to the coherent detection array 600, the coherent detection array 610 according to the present preferred embodiment may be configured in such a manner that, for the coherent detection units in each column, either the electrodes 55-1 or the electrodes 55-2 of the photodetectors 54-1 may be connected to a column-readout wiring, and similarly either the electrodes 55-3 or the electrodes 55-4 of the photodetectors 54-2 may be connected to a column-readout wiring.

[0121] Different from the coherent detection array 600, the coherent detection array 610 according to the present preferred embodiment may be configured in such a manner that the other electrodes of the photodetectors of the coherent detection units may be connected across different columns by row-encoding wirings instead of across different rows by column-readout wirings. For the coherent detection units 500 in each row of the coherent detection array 610, either the electrodes 55-1 or the electrodes 55-2 of the photodetectors 54-1 may be connected to a row-encoding wiring, and similarly either the electrodes 55-3 or the electrodes 55-4 of the photodetectors 54-2 may be connected to a row-encoding wiring. In some aspects, some of the row-encoding wirings may be combined to simplify the layout.

[0122] Referring to the coherent detection array 610 illustrated in FIG. 15. On one hand, for the coherent detection units 500-1, 500-5 and 500-9 in column 1, the electrodes 55-2 of the photodetectors 54-1 are connected to the column-readout wiring 63-1 and the electrodes 55-3 of the photodetectors 54-2 are connected to the column-readout wiring 64-1.

[0123] Similarly, for the coherent detection units **500-2**, **500-6** and **500-10** in column 2, the electrodes **55-2** of the photodetectors **54-1** are connected to the column-readout wiring **63-2** and the electrodes **55-3** of the photodetectors **54-2** are connected to the column-readout wiring **64-2**.

[0124] Similarly, for the coherent detection units **500-3**, **500-7** and **500-11** in column 3, the electrodes **55-2** of the photodetectors **54-1** are connected to the column-readout wiring **63-3** and the electrodes **55-3** of the photodetectors **54-2** are connected to the column-readout wiring **64-3**.

[0125] Similarly, for the coherent detection units **500-4**, **500-8** and **500-12** in column 4, the electrodes **55-2** of the photodetectors **54-1** are connected to the column-readout wiring **63-4** and the electrodes **55-3** of the photodetectors **54-2** are connected to the column-readout wiring **64-4**.

[0126] On the other hand, for the coherent detection units **500-1**, **500-2**, **500-3** and **500-4** in row 1, the electrodes **55-1** of the photodetectors **54-1** are connected to the row-encoding wiring **67-1** and the electrodes **55-4** of the photodetectors **54-2** are connected to the row-encoding wiring **68-1**.

[0127] Similarly, for the coherent detection units **500-5**, **500-6**, **500-7** and **500-8** in row 2, the electrodes **55-1** of the photodetectors **54-1** are connected to the row-encoding wiring **67-2** and the electrodes **55-4** of the photodetectors **54-2** are connected to the row-encoding wiring **68-2**.

[0128] Similarly, for the coherent detection units **500-9**, **500-10**, **500-11** and **500-12** in row 3, the electrodes **55-1** of the photodetectors **54-1** are connected to the row-encoding wiring **67-3** and the electrodes **55-4** of the photodetectors **54-2** are connected to the row-encoding wiring **68-3**.

[0129] The pads Pa in FIG. 15 are terminals of the column-readout wirings and the row-encoding wirings that may be connected to peripheral electrical circuits

Second Modified Example of Sixth Preferred Embodiment

[0130] FIG. 16 illustrates a plan view of the coherent detection array 620. The coherent detection array 620 is another modified example of the coherent detection array 600 according to the embodiment illustrated in FIG. 14.

[0131] The coherent detection array 620 illustrated in FIG. 16 is similar to the coherent detection array 600 illustrated in FIG. 14 with an essential difference of employing the coherent detection unit 510 according to the embodiment illustrated in FIG. 11 as a building block of the detection array, instead of the coherent detection unit 500 used in the coherent detection array 600. In some aspects of a rectilinear configuration, the coherent detection array may be configured in M rows and N columns with $M \times N$ coherent detection units. As an example, the embodiment of the coherent detection array 620 illustrated in FIG. 16 includes 12 coherent detection units 510-1, 510-2, 510-3, 510-4, 510-5, 510-6, 510-7, 510-8, 510-9, 510-10, 510-11 and 510-12 that are all coherent detection units 510 arranged in the format of 3 rows and 4 columns.

[0132] With the coherent detection units 510 employed, the row-encoding waveguides for the x -polarized and y -polarized light may be combined into one and the same local oscillator light $E_{LO,in\,m}$ with $m = 1, 2, \dots, M$, where M is the number of rows, may be used for the two polarizations.

[0133] For the coherent detection array 620 illustrated in FIG. 16, the LO light $E_{LO,in1}$ is introduced to the row-encoding waveguide 61-1 in row 1, the LO light $E_{LO,in2}$ is introduced to the row-encoding waveguide 61-3 in row 2, and the LO light $E_{LO,in3}$ is introduced to the row-encoding waveguide 61-5 in row 3.

Third Modified Example of Sixth Preferred Embodiment

[0134] FIG. 17 illustrates a plan view of the coherent detection array 630. The coherent detection array 630 is another modified example of the coherent detection array 600 according to the embodiment illustrated in FIG. 14.

[0135] The coherent detection array 630 combines the modifications made to the coherent detection array 600 according to the coherent detection array 610 in FIG. 15 and the coherent detection array 620 in FIG. 16. The coherent detection array 630 may be understood with reference

to the coherent detection arrays **610** and **620** according to the embodiments illustrated in FIGS. **15** and **16**, in conjunction with the following descriptions.

[0136] On one hand, similar to the coherent detection array **620**, the coherent detection array **630** employs the coherent detection unit **510** according to the embodiment illustrated in FIG. **11** as a building block of the detection array, instead of the coherent detection unit **500** used in the coherent detection arrays **600** and **610**.

[0137] With the coherent detection units **510** employed, the row-encoding waveguides for the x -polarized and y -polarized light may be combined into one and the same local oscillator light $E_{LO,in\,m}$ with $m = 1, 2, \dots, M$, where M is the number of rows, may be used for the two polarizations.

[0138] For the coherent detection array **630** illustrated in FIG. **17**, the LO light $E_{LO,in1}$ is introduced to the row-encoding waveguide **61-1** in row 1, the LO light $E_{LO,in2}$ is introduced to the row-encoding waveguide **61-3** in row 2, and the LO light $E_{LO,in3}$ is introduced to the row-encoding waveguide **61-5** in row 3.

[0139] On the other hand, similar to the coherent detection array **610**, the coherent detection array **630** may be configured in such a manner that, for the coherent detection units **510** in each column of the detection array, either the electrodes **55-1** or the electrodes **55-2** of the photodetectors **54-1** may be connected to a column-readout wiring across the rows of that column and either the electrodes **55-3** or the electrodes **55-4** of the photodetectors **54-2** may be connected to a column-readout wiring across the rows of that column, while the other electrodes of the photodetectors **54-1** and **54-2** of the coherent detection units **510** in each row of the detection array may be connected to row-encoding wirings, or a common row-encoding wiring, across the columns of that row.

[0140] Referring to the coherent detection array **630** illustrated in FIG. **17**. On one hand, for the coherent detection units **510-1**, **510-5** and **510-9** in column 1, the electrodes **55-2** of the photodetectors **54-1** are connected to the column-readout wiring **63-1** and the electrodes **55-3** of the photodetectors **54-2** are connected to the column-readout wiring **64-1**.

[0141] Similarly, for the coherent detection units **510-2**, **510-6** and **510-10** in column 2, the electrodes **55-2** of the photodetectors **54-1** are connected to the column-readout wiring **63-2**

and the electrodes **55-3** of the photodetectors **54-2** are connected to the column-readout wiring **64-2**.

[0142] Similarly, for the coherent detection units **510-3**, **510-7** and **510-11** in column 3, the electrodes **55-2** of the photodetectors **54-1** are connected to the column-readout wiring **63-3** and the electrodes **55-3** of the photodetectors **54-2** are connected to the column-readout wiring **64-3**.

[0143] Similarly, for the coherent detection units **510-4**, **510-8** and **510-12** in column 4, the electrodes **55-2** of the photodetectors **54-1** are connected to the column-readout wiring **63-4** and the electrodes **55-3** of the photodetectors **54-2** are connected to the column-readout wiring **64-4**.

[0144] On the other hand, for the coherent detection units **510-1**, **510-2**, **510-3** and **510-4** in row 1, the electrodes **55-1** of the photodetectors **54-1** are connected to the row-encoding wiring **67-1** and the electrodes **55-4** of the photodetectors **54-2** are connected to the row-encoding wiring **68-1**.

[0145] Similarly, for the coherent detection units **510-5**, **510-6**, **510-7** and **510-8** in row 2, the electrodes **55-1** of the photodetectors **54-1** are connected to the row-encoding wiring **67-2** and the electrodes **55-4** of the photodetectors **54-2** are connected to the row-encoding wiring **68-2**.

[0146] Similarly, for the coherent detection units **510-9**, **510-10**, **510-11** and **510-12** in row 3, the electrodes **55-1** of the photodetectors **54-1** are connected to the row-encoding wiring **67-3** and the electrodes **55-4** of the photodetectors **54-2** are connected to the row-encoding wiring **68-3**.

Fourth Modified Example of Sixth Preferred Embodiment

[0147] FIG. 18 illustrates a plan view of the coherent detection array **640**. The coherent detection array **640** is another modified example of the coherent detection array **600** according to the embodiment illustrated in FIG. 14.

[0148] The coherent detection array **640** illustrated in FIG. 18 is similar to the coherent detection array **600** illustrated in FIG. 14 with an essential difference of employing the coherent

detection unit **520** according to the embodiment illustrated in FIG. **12** as a building block of the detection array, instead of the coherent detection unit **500** used in the coherent detection array **600**. In some aspects of a rectilinear configuration, the coherent detection array may be configured in M rows and N columns with $M \times N$ coherent detection units. As an example, the embodiment of the coherent detection array **640** illustrated in FIG. **18** includes 12 coherent detection units **520-1**, **520-2**, **520-3**, **520-4**, **520-5**, **520-6**, **520-7**, **520-8**, **520-9**, **520-10**, **520-11** and **520-12** that are all coherent detection units **520** arranged in the format of 3 rows and 4 columns.

Fifth Modified Example of Sixth Preferred Embodiment

[0149] FIG. **19** illustrates a plan view of the coherent detection array **650**. The coherent detection array **650** is another modified example of the coherent detection array **600** according to the embodiment illustrated in FIG. **14**.

[0150] The coherent detection array **650** combines the modifications made to the coherent detection array **600** according to the coherent detection array **610** in FIG. **15** and the coherent detection array **640** in FIG. **18**. The coherent detection array **650** may be understood with reference to the coherent detection arrays **610** and **640** according to the embodiments illustrated in FIGS. **15** and **18**, in conjunction with the following descriptions.

[0151] On one hand, similar to the coherent detection array **640**, the coherent detection array **650** employs the coherent detection unit **520** according to the embodiment illustrated in FIG. **12** as a building block of the detection array, instead of the coherent detection unit **500** used in the coherent detection arrays **600** and **610**.

[0152] On the other hand, similar to the coherent detection array **610**, the coherent detection array **650** may be configured in such a manner that, for the coherent detection units **520** in each column of the detection array, either the electrodes **55-1** or the electrodes **55-2** of the photodetectors **54-1** may be connected to a column-readout wiring across the rows of that column and either the electrodes **55-3** or the electrodes **55-4** of the photodetectors **54-2** may be connected to a column-readout wiring across the rows of that column, while the other electrodes of the photodetectors **54-1** and **54-2** of the coherent detection units **520** in each row of the detection array

may be connected to row-encoding wirings, or a common row-encoding wiring, across the columns of that row.

[0153] Referring to the coherent detection array 650 illustrated in FIG. 19. On one hand, for the coherent detection units 520-1, 520-5 and 520-9 in column 1, the electrodes 55-2 of the photodetectors 54-1 are connected to the column-readout wiring 63-1 and the electrodes 55-3 of the photodetectors 54-2 are connected to the column-readout wiring 64-1.

[0154] Similarly, for the coherent detection units 520-2, 520-6 and 520-10 in column 2, the electrodes 55-2 of the photodetectors 54-1 are connected to the column-readout wiring 63-2 and the electrodes 55-3 of the photodetectors 54-2 are connected to the column-readout wiring 64-2.

[0155] Similarly, for the coherent detection units 520-3, 520-7 and 520-11 in column 3, the electrodes 55-2 of the photodetectors 54-1 are connected to the column-readout wiring 63-3 and the electrodes 55-3 of the photodetectors 54-2 are connected to the column-readout wiring 64-3.

[0156] Similarly, for the coherent detection units 520-4, 520-8 and 520-12 in column 4, the electrodes 55-2 of the photodetectors 54-1 are connected to the column-readout wiring 63-4 and the electrodes 55-3 of the photodetectors 54-2 are connected to the column-readout wiring 64-4.

[0157] On the other hand, for the coherent detection units 520-1, 520-2, 520-3 and 520-4 in row 1, the electrodes 55-1 of the photodetectors 54-1 are connected to the row-encoding wiring 67-1 and the electrodes 55-4 of the photodetectors 54-2 are connected to the row-encoding wiring 68-1.

[0158] Similarly, for the coherent detection units 520-5, 520-6, 520-7 and 520-8 in row 2, the electrodes 55-1 of the photodetectors 54-1 are connected to the row-encoding wiring 67-2 and the electrodes 55-4 of the photodetectors 54-2 are connected to the row-encoding wiring 68-2.

[0159] Similarly, for the coherent detection units 520-9, 520-10, 520-11 and 520-12 in row 3, the electrodes 55-1 of the photodetectors 54-1 are connected to the row-encoding wiring 67-3

and the electrodes **55-4** of the photodetectors **54-2** are connected to the row-encoding wiring **68-3**.

Sixth Modified Example of Sixth Preferred Embodiment

[0160] FIG. 20 illustrates a plan view of the coherent detection array **660**. The coherent detection array **660** is another modified example of the coherent detection array **600** according to the embodiment illustrated in FIG. 14.

[0161] The coherent detection array **660** illustrated in FIG. 20 is similar to the coherent detection array **600** illustrated in FIG. 14 with an essential difference of employing the coherent detection unit **530** according to the embodiment illustrated in FIG. 13 as a building block of the detection array, instead of the coherent detection unit **500** used in the coherent detection array **600**. In some aspects of a rectilinear configuration, the coherent detection array may be configured in M rows and N columns with $M \times N$ coherent detection units. As an example, the embodiment of the coherent detection array **660** illustrated in FIG. 20 includes 12 coherent detection units **530-1**, **530-2**, **530-3**, **530-4**, **530-5**, **530-6**, **530-7**, **530-8**, **530-9**, **530-10**, **530-11** and **530-12** that are all coherent detection units **530** arranged in the format of 3 rows and 4 columns.

[0162] With the coherent detection units **530** employed, the row-encoding waveguides for the x -polarized and y -polarized light may be combined into one and the same local oscillator light $E_{LO,in\ m}$ with $m = 1, 2, \dots, M$, where M is the number of rows, may be used for the two polarizations.

[0163] For the coherent detection array **660** illustrated in FIG. 20, the LO light $E_{LO,in1}$ is introduced to the row-encoding waveguide **61-1** in row 1, the LO light $E_{LO,in2}$ is introduced to the row-encoding waveguide **61-3** in row 2, and the LO light $E_{LO,in3}$ is introduced to the row-encoding waveguide **61-5** in row 3.

Seventh Modified Example of Sixth Preferred Embodiment

[0164] FIG. 21 illustrates a plan view of the coherent detection array **670**. The coherent detection array **670** is another modified example of the coherent detection array **600** according to the embodiment illustrated in FIG. 14.

[0165] The coherent detection array **670** combines the modifications made to the coherent detection array **600** according to the coherent detection array **610** in FIG. **15** and the coherent detection array **660** in FIG. **20**. The coherent detection array **670** may be understood with reference to the coherent detection arrays **610** and **660** according to the embodiments illustrated in FIGS. **15** and **20**, in conjunction with the following descriptions.

[0166] On one hand, similar to the coherent detection array **660**, the coherent detection array **670** employs the coherent detection unit **530** according to the embodiment illustrated in FIG. **13** as a building block of the detection array, instead of the coherent detection unit **500** used in the coherent detection arrays **600** and **610**.

[0167] With the coherent detection units **530** employed, the row-encoding waveguides for the x -polarized and y -polarized light may be combined into one and the same local oscillator light $E_{LO,in\,m}$ with $m = 1, 2, \dots, M$, where M is the number of rows, may be used for the two polarizations.

[0168] For the coherent detection array **670** illustrated in FIG. **21**, the LO light $E_{LO,in1}$ is introduced to the row-encoding waveguide **61-1** in row 1, the LO light $E_{LO,in2}$ is introduced to the row-encoding waveguide **61-3** in row 2, and the LO light $E_{LO,in3}$ is introduced to the row-encoding waveguide **61-5** in row 3.

[0169] On the other hand, similar to the coherent detection array **610**, the coherent detection array **670** may be configured in such a manner that, for the coherent detection units **530** in each column of the detection array, either the electrodes **55-1** or the electrodes **55-2** of the photodetectors **54-1** may be connected to a column-readout wiring across the rows of that column and either the electrodes **55-3** or the electrodes **55-4** of the photodetectors **54-2** may be connected to a column-readout wiring across the rows of that column, while the other electrodes of the photodetectors **54-1** and **54-2** of the coherent detection units **530** in each row of the detection array may be connected to row-encoding wirings, or a common row-encoding wiring, across the columns of that row.

[0170] Referring to the coherent detection array **670** illustrated in FIG. **21**. On one hand, for the coherent detection units **530-1**, **530-5** and **530-9** in column 1, the electrodes **55-2** of the

photodetectors **54-1** are connected to the column-readout wiring **63-1** and the electrodes **55-3** of the photodetectors **54-2** are connected to the column-readout wiring **64-1**.

[0171] Similarly, for the coherent detection units **530-2**, **530-6** and **530-10** in column 2, the electrodes **55-2** of the photodetectors **54-1** are connected to the column-readout wiring **63-2** and the electrodes **55-3** of the photodetectors **54-2** are connected to the column-readout wiring **64-2**.

[0172] Similarly, for the coherent detection units **530-3**, **530-7** and **530-11** in column 3, the electrodes **55-2** of the photodetectors **54-1** are connected to the column-readout wiring **63-3** and the electrodes **55-3** of the photodetectors **54-2** are connected to the column-readout wiring **64-3**.

[0173] Similarly, for the coherent detection units **530-4**, **530-8** and **530-12** in column 4, the electrodes **55-2** of the photodetectors **54-1** are connected to the column-readout wiring **63-4** and the electrodes **55-3** of the photodetectors **54-2** are connected to the column-readout wiring **64-4**.

[0174] On the other hand, for the coherent detection units **530-1**, **530-2**, **530-3** and **530-4** in row 1, the electrodes **55-1** of the photodetectors **54-1** are connected to the row-encoding wiring **67-1** and the electrodes **55-4** of the photodetectors **54-2** are connected to the row-encoding wiring **68-1**.

[0175] Similarly, for the coherent detection units **530-5**, **530-6**, **530-7** and **530-8** in row 2, the electrodes **55-1** of the photodetectors **54-1** are connected to the row-encoding wiring **67-2** and the electrodes **55-4** of the photodetectors **54-2** are connected to the row-encoding wiring **68-2**.

[0176] Similarly, for the coherent detection units **530-9**, **530-10**, **530-11** and **530-12** in row 3, the electrodes **55-1** of the photodetectors **54-1** are connected to the row-encoding wiring **67-3** and the electrodes **55-4** of the photodetectors **54-2** are connected to the row-encoding wiring **68-3**.

Seventh Preferred Embodiment

[0177] Two examples of coherent detection units **700** and **710** according to the present preferred embodiment will be described with reference to FIGS. **22** and **23**.

[0178] FIG. 22 illustrates a plan view of the coherent detection unit 700. The coherent detection unit 700 illustrated in FIG. 22 is configured to include a polarized-light separating free-space-to-waveguide coupler 71, optical couplers 72-1, 72-2, 72-3, and 72-4, waveguides 73-1, 73-2, 73-3, 73-4, 73-5, 73-6, 73-7, 73-8, 73-9 and 73-10, photodetectors 74-1, 74-2, 74-3 and 74-4, and electrodes 75-1, 75-2, 75-3, 75-4, 75-5, 75-6, 75-7 and 75-8. The coherent detection unit 700 may also be configured to include additional components, such as one or more modulators and/or heaters, which may be used to modulate or modify the properties of the coherent detection unit. These additional components are not shown in FIG. 22. The coherent detection unit 700 may be integrated on a substrate 76 using optical waveguide technology.

[0179] The coherent detection unit 700 is a modified version of the coherent detection unit 100 illustrated in FIG. 1. The coherent detection unit 700 is configured to detect incoming signal light that may be multiplexed with polarizations in the x and y directions in such a way that the two polarization components may be measured separately. The coherent detection unit 700 may be understood with reference to the coherent detection unit 100 according to the embodiment illustrated in FIG. 1, in conjunction with the following descriptions.

[0180] The coherent detection unit 700 is constructed by combining coherent detection sub-units 101 and 102 (see FIG. 22), each of which is similar to the coherent detection unit 100, with a polarized-light separating free-space-to-waveguide coupler 71 replacing the free-space-to-waveguide coupler 11 of the coherent detection unit 100. The coherent detection sub-unit 101 is configured to include a polarized-light separating free-space-to-waveguide coupler 71, optical couplers 72-1 and 72-2, waveguides 73-1, 73-2, 73-3, 73-4 and 73-5, photodetectors 74-1 and 74-2, and electrodes 75-1, 75-2, 75-3 and 75-4. The coherent detection sub-unit 102 is configured to include the same polarized-light separating free-space-to-waveguide coupler 71, optical couplers 72-3 and 72-4, waveguides 73-6, 73-7, 73-8, 73-9 and 73-10, photodetectors 74-3 and 74-4, and electrodes 75-5, 75-6, 75-7 and 75-8. In such configuration, the polarized-light separating free-space-to-waveguide coupler 71 is a common component of the two coherent detection sub-units 101 and 102.

[0181] In FIG. 22, the waveguide 73-1 has one end through which the local oscillator light $E_{LO,in\ x}$ may be introduced and the other end through which the local oscillator light $E_{LO,out\ x}$ may be transmitted, and the waveguide 73-10 has one end through which the local oscillator light

$E_{LO,in\ y}$ may be introduced and the other end through which the local oscillator light $E_{LO,out\ y}$ may be transmitted.

[0182] The coherent detection unit **700** uses the polarized-light separating free-space-to-waveguide coupler **71** to receive the signal light $E_{Sig,in}$ that may comprise multiplexed x-polarized light and y-polarized light. The signal light $E_{Sig,in}$ may be received and separated into x-polarized light and y-polarized light by the polarized-light separating free-space-to-waveguide coupler **71**. On one hand, the x-polarized light may be carried into the coherent detection sub-unit **101** through the waveguide **73-3** and may result in photocurrents in the electrodes **75-1**, **75-2**, **75-3** and **75-4** when detected by the photodetectors **74-1** and **74-2**. On the other hand, the y-polarized light may be carried into the coherent detection sub-unit **102** through the waveguide **73-7** and may result in photocurrents in the electrodes **75-5**, **75-6**, **75-7** and **75-8** when detected by the photodetectors **74-3** and **74-4**.

Modified Example of Seventh Preferred Embodiment

[0183] FIG. **23** illustrates a plan view of the coherent detection unit **710**. The coherent detection unit **710** illustrated in FIG. **23** is a modified example of the coherent detection unit **700** according to the embodiment illustrated in FIG. **22**.

[0184] The coherent detection unit **710** in FIG. **23** is similar to the coherent detection unit **700** in FIG. **22** with an essential difference of moving the optical coupler **72-3** to the waveguide **73-1** to couple the same local oscillator light from the waveguide **73-1** to the waveguide **73-6** as the local oscillator light to the waveguide **73-2**. In this way, the x-polarized and y-polarized components of the signal light coupled into the detection unit **710** may be mixed with the same local oscillator light $E_{LO,in}$. The waveguide **73-10** may be removed accordingly.

Eighth Preferred Embodiment

[0185] Four examples of coherent detection arrays **800**, **810**, **820** and **830** according to the present preferred embodiment will be described with reference to FIGS. **24**, **25**, **26**, and **27**.

[0186] FIG. 24 illustrates a plan view of the coherent detection array 800. The coherent detection array 800 is configured to include plural units of the coherent detection unit 700 according to the embodiment illustrated in FIG. 22. In some aspects, the coherent detection array 800 may include other embodiments of the coherent detection units. In some aspects, the coherent detection array 800 may be constructed by concatenating plural units of the coherent detection unit 700 in a rectilinear configuration. In other aspects, embodiments of the coherent detection array may be constructed by concatenating plural units of the coherent detection unit 700 in geometries other than the rectilinear configuration. The coherent detection array 800 may be integrated on a substrate 86 using optical waveguide technology.

[0187] The coherent detection array 800 illustrated in FIG. 24 is similar to the coherent detection array 200 illustrated in FIG. 2 with an essential difference of employing the coherent detection unit 700 according to the embodiment illustrated in FIG. 22 as a building block of the detection array, instead of the coherent detection unit 100 used in the coherent detection array 200. In some aspects of a rectilinear configuration, the coherent detection array may be configured in M rows and N columns with $M \times N$ coherent detection units. As an example, the embodiment of the coherent detection array 800 illustrated in FIG. 24 includes 6 coherent detection units 700-1, 700-2, 700-3, 700-4, 700-5 and 700-6 that are all coherent detection units 700 arranged in the format of 2 rows and 3 columns.

[0188] The coherent detection array 800 may be understood with reference to the coherent detection array 200 according to the embodiment illustrated in FIG. 2, in conjunction with the following descriptions.

[0189] In some aspects with the coherent detection units 700 configured to detect incoming signal light that may be multiplexed with polarizations in the x and y directions, each row of a coherent detection array 800 may be configured to comprise a row-encoding waveguide for the x -polarized light and a row-encoding waveguide for the y -polarized light, with separate LO light introduced to each row-encoding waveguide. The series of the waveguides 73-1 and 73-10 in a row of connected coherent detection units 700 in the coherent detection array 800 constitute row-encoding waveguides of that row (see FIGS. 22 and 24). The LO light in the row-encoding waveguide for the x polarization may be coupled to the connected coherent detection units 700 through the optical couplers 72-1, and the LO light in the row-encoding waveguide for the y

polarization may be coupled to the connected coherent detection units **700** through the optical couplers **72-3** (see FIGS. **22** and **24**).

[0190] The electric fields of the LO light introduced to the row-encoding waveguides of the coherent detection array are $E_{LO,in\ m\ x}$ and $E_{LO,in\ m\ y}$ with $m = 1, 2, \dots, M$, where M is the number of rows of the detection array. The corresponding transmitted LO fields out of the waveguides are $E_{LO,out\ mx}$ and $E_{LO,out\ my}$. The LO fields $E_{LO,in\ m\ x}$ and $E_{LO,in\ m\ y}$ for different m may have the same or different optical frequencies, the same or different magnitudes, and the same or different relative phases.

[0191] For the coherent detection array **800** illustrated in FIG. **24**, the LO fields $E_{LO,in1x}$ and $E_{LO,in1y}$ are introduced respectively to the row-encoding waveguides **81-1** and **81-2** in row 1, and the LO fields $E_{LO,in2x}$ and $E_{LO,in2y}$ are introduced respectively to the row-encoding waveguides **81-3** and **81-4** in row 2.

[0192] In some aspects, a coherent detection array according to the present preferred embodiment may be constructed in such a manner that, for the coherent detection units in each column, the electrodes **75-1** and **75-2** of the photodetectors **74-1**, the electrodes **75-3** and **75-4** of the photodetectors **74-2**, the electrodes **75-5** and **75-6** of the photodetectors **74-3**, and the electrodes **75-7** and **75-8** of the photodetectors **74-4** may be connected to separate column-readout wirings. In other aspects, either the electrodes **75-1** or the electrodes **75-2** of the photodetectors **74-1** and either the electrodes **75-3** or the electrodes **75-4** of the photodetectors **74-2** may be connected to a common column-readout wiring instead of separate column-readout wirings, and either the electrodes **75-5** or the electrodes **75-6** of the photodetectors **74-3** and either the electrodes **75-7** or the electrodes **75-8** of the photodetectors **74-4** may be connected to a common column-readout wiring instead of separate column-readout wirings. In further aspects, some of the column-readout wirings may be combined to simplify the layout.

[0193] For the coherent detection units **700-1** and **700-4** in column 1 of the illustration in FIG. **24**, the electrodes **75-1** of the photodetectors **74-1** are connected to the column-readout wiring **82-1**, the electrodes **75-3** of the photodetectors **74-2** are connected to the column-readout wiring **83-1**, the electrodes **75-5** of the photodetectors **74-3** are connected to the column-readout wiring **88-1**, the electrodes **75-7** of the photodetectors **74-4** are connected to the column-readout wiring

89-1, the electrodes **75-2** of the photodetectors **74-1** and the electrodes **75-4** of the photodetectors **74-2** are connected to the common column-readout wiring **84-1**, and the electrodes **75-6** of the photodetectors **74-3** and the electrodes **75-8** of the photodetectors **74-4** are connected to the common column-readout wiring **87-1**.

[0194] Similarly, for the coherent detection units **700-2** and **700-5** in column 2, the electrodes **75-1** of the photodetectors **74-1** are connected to the column-readout wiring **82-2**, the electrodes **75-3** of the photodetectors **74-2** are connected to the column-readout wiring **83-2**, the electrodes **75-5** of the photodetectors **74-3** are connected to the column-readout wiring **88-2**, the electrodes **75-7** of the photodetectors **74-4** are connected to the column-readout wiring **89-2**, the electrodes **75-2** of the photodetectors **74-1** and the electrodes **75-4** of the photodetectors **74-2** are connected to the common column-readout wiring **84-2**, and the electrodes **75-6** of the photodetectors **74-3** and the electrodes **75-8** of the photodetectors **74-4** are connected to the common column-readout wiring **87-2**.

[0195] Similarly, for the coherent detection units **700-3** and **700-6** in column 3, the electrodes **75-1** of the photodetectors **74-1** are connected to the column-readout wiring **82-3**, the electrodes **75-3** of the photodetectors **74-2** are connected to the column-readout wiring **83-3**, the electrodes **75-5** of the photodetectors **74-3** are connected to the column-readout wiring **88-3**, the electrodes **75-7** of the photodetectors **74-4** are connected to the column-readout wiring **89-3**, the electrodes **75-2** of the photodetectors **74-1** and the electrodes **75-4** of the photodetectors **74-2** are connected to the common column-readout wiring **84-3**, and the electrodes **75-6** of the photodetectors **74-3** and the electrodes **75-8** of the photodetectors **74-4** are connected to the common column-readout wiring **87-3**.

[0196] Similar to FIG. 2, the pads **Pa** in FIG. 24 are output terminals of the column-readout wirings that may be connected to peripheral readout circuits.

First Modified Example of Eighth Preferred Embodiment

[0197] FIG. 25 illustrates a plan view of the coherent detection array **810**. The coherent detection array **810** is a modified example of the coherent detection array **800** according to the embodiment illustrated in FIG. 24. Similar to the coherent detection array **800**, the coherent

detection array **810** may be configured to include plural units of the coherent detection unit **700** according to the embodiment illustrated in FIG. **22**. Each row of a coherent detection array **810** may be constructed by concatenating a series of the coherent detection units **700** using the waveguides **73-1** (see FIG. **22**). Plural rows of the coherent detection units **700** may be concatenated in series by electrical conducting paths to form a detection array. As an example, the embodiment of the coherent detection array **810** illustrated in FIG. **25** includes 6 coherent detection units **700-1**, **700-2**, **700-3**, **700-4**, **700-5** and **700-6** that are all coherent detection units **700** arranged in the format of 2 rows and 3 columns.

[0198] Similar to the coherent detection array **800**, the coherent detection array **810** according to the present preferred embodiment may be configured in such a manner that, for the coherent detection units in each column, either the electrodes **75-1** or the electrodes **75-2** of the photodetectors **74-1** may be connected to a column-readout wiring, either the electrodes **75-3** or the electrodes **75-4** of the photodetectors **74-2** may be connected to a column-readout wiring, either the electrodes **75-5** or the electrodes **75-6** of the photodetectors **74-3** may be connected to a column-readout wiring, and either the electrodes **75-7** or the electrodes **75-8** of the photodetectors **74-4** may be connected to a column-readout wiring.

[0199] Different from the coherent detection array **800**, the coherent detection array **810** according to the present preferred embodiment may be configured in such a manner that the other electrodes of the photodetectors of the coherent detection units may be connected across different columns by row-encoding wirings instead of across different rows by column-readout wirings. In some aspects, for the coherent detection units **700** in each row of the coherent detection array **810**, either the electrodes **75-1** or the electrodes **75-2** of the photodetectors **74-1** may be connected to a row-encoding wiring, either the electrodes **75-3** or the electrodes **75-4** of the photodetectors **74-2** may be connected to a row-encoding wiring, either the electrodes **75-5** or the electrodes **75-6** of the photodetectors **74-3** may be connected to a row-encoding wiring, and either the electrodes **75-7** or the electrodes **75-8** of the photodetectors **74-4** may be connected to a row-encoding wiring. In other aspects, either the electrodes **75-1** or the electrodes **75-2** of the photodetectors **74-1** and either the electrodes **75-3** or the electrodes **75-4** of the photodetectors **74-2** may be connected to a common row-encoding wiring instead of separate row-encoding wirings, and either the electrodes **75-5** or the electrodes **75-6** of the photodetectors **74-3** and either the electrodes **75-7** or the

electrodes 75-8 of the photodetectors 74-4 may be connected to a common row-encoding wiring instead of separate row-encoding wirings. In further aspects, some of the row-encoding wirings may be combined, and/or some of the column-readout wirings may be combined to simplify the layout.

[0200] Referring to the coherent detection array 810 illustrated in FIG. 25. On one hand, for the coherent detection units 700-1 and 700-4 in column 1, the electrodes 75-1 of the photodetectors 74-1 are connected to the column-readout wiring 82-1, the electrodes 75-3 of the photodetectors 74-2 are connected to the column-readout wiring 83-1, the electrodes 75-5 of the photodetectors 74-3 are connected to the column-readout wiring 88-1, and the electrodes 75-7 of the photodetectors 74-4 are connected to the column-readout wiring 89-1.

[0201] Similarly, for the coherent detection units 700-2 and 700-5 in column 2, the electrodes 75-1 of the photodetectors 74-1 are connected to the column-readout wiring 82-2, the electrodes 75-3 of the photodetectors 74-2 are connected to the column-readout wiring 83-2, the electrodes 75-5 of the photodetectors 74-3 are connected to the column-readout wiring 88-2, and the electrodes 75-7 of the photodetectors 74-4 are connected to the column-readout wiring 89-2.

[0202] Similarly, for the coherent detection units 700-3 and 700-6 in column 3, the electrodes 75-1 of the photodetectors 74-1 are connected to the column-readout wiring 82-3, the electrodes 75-3 of the photodetectors 74-2 are connected to the column-readout wiring 83-3, the electrodes 75-5 of the photodetectors 74-3 are connected to the column-readout wiring 88-3, and the electrodes 75-7 of the photodetectors 74-4 are connected to the column-readout wiring 89-3.

[0203] On the other hand, for the coherent detection units 700-1, 700-2 and 700-3 in row 1, the electrodes 75-2 of the photodetectors 74-1 and the electrodes 75-4 of the photodetectors 74-2 are connected to the common row-encoding wiring 811-1, and the electrodes 75-6 of the photodetectors 74-3 and the electrodes 75-8 of the photodetectors 74-4 are connected to the common row-encoding wiring 812-1.

[0204] Similarly, for the coherent detection units 700-4, 700-5 and 700-6 in row 2, the electrodes 75-2 of the photodetectors 74-1 and the electrodes 75-4 of the photodetectors 74-2 are connected to the common row-encoding wiring 811-2, and the electrodes 75-6 of the

photodetectors **74-3** and the electrodes **75-8** of the photodetectors **74-4** are connected to the common row-encoding wiring **812-2**.

[0205] The pads Pa in FIG. **25** are terminals of the column-readout wirings and the row-encoding wirings that may be connected to peripheral electrical circuits

Second Modified Example of Eighth Preferred Embodiment

[0206] FIG. **26** illustrates a plan view of the coherent detection array **820**. The coherent detection array **820** is another modified example of the coherent detection array **800** according to the embodiment illustrated in FIG. **24**.

[0207] The coherent detection array **820** illustrated in FIG. **26** is similar to the coherent detection array **800** illustrated in FIG. **24** with an essential difference of employing the coherent detection unit **710** according to the embodiment illustrated in FIG. **23** as a building block of the detection array, instead of the coherent detection unit **700** used in the coherent detection array **800**. In some aspects of a rectilinear configuration, the coherent detection array may be configured in M rows and N columns with $M \times N$ coherent detection units. As an example, the embodiment of the coherent detection array **820** illustrated in FIG. **26** includes 6 coherent detection units **710-1**, **710-2**, **710-3**, **710-4**, **710-5** and **710-6** that are all coherent detection units **710** arranged in the format of 2 rows and 3 columns.

[0208] With the coherent detection units **710** employed, the row-encoding waveguides for the x -polarized and y -polarized light may be combined into one and the same local oscillator light $E_{LO,in\ m}$ with $m = 1, 2, \dots, M$, where M is the number of rows, may be used for the two polarizations.

[0209] For the coherent detection array **820** illustrated in FIG. **26**, the LO light $E_{LO,in1}$ is introduced to the row-encoding waveguide **81-1** in row 1, and the LO light $E_{LO,in2}$ is introduced to the row-encoding waveguide **81-3** in row 2.

Third Modified Example of Eighth Preferred Embodiment

[0210] FIG. 27 illustrates a plan view of the coherent detection array 830. The coherent detection array 830 is another modified example of the coherent detection array 800 according to the embodiment illustrated in FIG. 24.

[0211] The coherent detection array 830 combines the modifications made to the coherent detection array 800 according to the coherent detection array 810 in FIG. 25 and the coherent detection array 820 in FIG. 26. The coherent detection array 830 may be understood with reference to the coherent detection arrays 810 and 820 according to the embodiments illustrated in FIGS. 25 and 26, in conjunction with the following descriptions.

[0212] On one hand, similar to the coherent detection array 820, the coherent detection array 830 employs the coherent detection unit 710 according to the embodiment illustrated in FIG. 23 as a building block of the detection array, instead of the coherent detection unit 700 used in the coherent detection arrays 800 and 810.

[0213] With the coherent detection units 710 employed, the row-encoding waveguides for the x -polarized and y -polarized light may be combined into one and the same local oscillator light $E_{LO,in\,m}$ with $m = 1, 2, \dots, M$, where M is the number of rows, may be used for the two polarizations.

[0214] For the coherent detection array 830 illustrated in FIG. 27, the LO light $E_{LO,in1}$ is introduced to the row-encoding waveguide 81-1 in row 1, and the LO light $E_{LO,in2}$ is introduced to the row-encoding waveguide 81-3 in row 2.

[0215] On the other hand, similar to the coherent detection array 810, the coherent detection array 830 may be configured in such a manner that, for the coherent detection units 710 in each column of the detection array, either the electrodes 75-1 or the electrodes 75-2 of the photodetectors 74-1 may be connected to a column-readout wiring, either the electrodes 75-3 or the electrodes 75-4 of the photodetectors 74-2 may be connected to a column-readout wiring, either the electrodes 75-5 or the electrodes 75-6 of the photodetectors 74-3 may be connected to a column-readout wiring, and either the electrodes 75-7 or the electrodes 75-8 of the photodetectors 74-4 may be connected to a column-readout wiring, while the other electrodes of the photodetectors 74-1, 74-2, 74-3 and 74-4 of the coherent detection units 710 in each row of the detection array may be connected to row-encoding wirings across the columns of that row. In some

aspects, some of the row-encoding wirings may be combined, and/or some of the column-readout wirings may be combined to simplify the layout.

[0216] Referring to the coherent detection array 830 illustrated in FIG. 27. On one hand, for the coherent detection units 710-1 and 710-4 in column 1, the electrodes 75-1 of the photodetectors 74-1 are connected to the column-readout wiring 82-1, the electrodes 75-3 of the photodetectors 74-2 are connected to the column-readout wiring 83-1, the electrodes 75-5 of the photodetectors 74-3 are connected to the column-readout wiring 88-1, and the electrodes 75-7 of the photodetectors 74-4 are connected to the column-readout wiring 89-1.

[0217] Similarly, for the coherent detection units 710-2 and 710-5 in column 2, the electrodes 75-1 of the photodetectors 74-1 are connected to the column-readout wiring 82-2, the electrodes 75-3 of the photodetectors 74-2 are connected to the column-readout wiring 83-2, the electrodes 75-5 of the photodetectors 74-3 are connected to the column-readout wiring 88-2, and the electrodes 75-7 of the photodetectors 74-4 are connected to the column-readout wiring 89-2.

[0218] Similarly, for the coherent detection units 710-3 and 710-6 in column 3, the electrodes 75-1 of the photodetectors 74-1 are connected to the column-readout wiring 82-3, the electrodes 75-3 of the photodetectors 74-2 are connected to the column-readout wiring 83-3, the electrodes 75-5 of the photodetectors 74-3 are connected to the column-readout wiring 88-3, and the electrodes 75-7 of the photodetectors 74-4 are connected to the column-readout wiring 89-3.

[0219] On the other hand, for the coherent detection units 710-1, 710-2 and 710-3 in row 1, the electrodes 75-2 of the photodetectors 74-1 and the electrodes 75-4 of the photodetectors 74-2 are connected to the common row-encoding wiring 811-1, and the electrodes 75-6 of the photodetectors 74-3 and the electrodes 75-8 of the photodetectors 74-4 are connected to the common row-encoding wiring 812-1.

[0220] Similarly, for the coherent detection units 710-4, 710-5 and 710-6 in row 2, the electrodes 75-2 of the photodetectors 74-1 and the electrodes 75-4 of the photodetectors 74-2 are connected to the common row-encoding wiring 811-2, and the electrodes 75-6 of the photodetectors 74-3 and the electrodes 75-8 of the photodetectors 74-4 are connected to the common row-encoding wiring 812-2.

Multiplexing Methods

[0221] The signal multiplexing methods that may be applied to the coherent detection array in the present invention will be described in the following. In some aspects, the signal multiplexing methods may be applied to the embodiments of the configurations of the coherent detection array in the present invention. In other aspects, the signal multiplexing methods may also be applied to other detection array configurations and designs not mentioned.

[0222] The signal multiplexing methods comprise methods leveraging the extra degrees of freedom of the coherent detection array. These multiplexing methods may be categorized into optical and electrical domains. These methods may include those enabled by the local oscillator and those related to the properties and responses of the components of the PIC-based detection array.

[0223] Multiplexing in the optical domain may include the manipulation of the properties of the local oscillator and the optical waveguides of the detection array. Multiplexing through the LO may be enabled by controlling the amplitude, frequency and phase of the LO light at each detection unit or groups of detection units of the detection array. The photocurrents generated may be multiplexed to form multiplexed electrical readout signals. The amplitudes, frequencies and phases of the LO of the detection units may also be temporally modulated so that the multiplexed electrical readout signals may vary in time accordingly.

[0224] Multiplexing through the waveguides of the detection array may be enabled by controlling the refractive index of the waveguides of the detection array electrically, thermally, or optically. Methods to control the refractive index of the waveguides electrically may include those utilizing the electro-optic (EO) effect. Methods to control the refractive index of the waveguides thermally may include those utilizing the thermo-optic (TO) effect. Methods to control the refractive index of the waveguides optically may include those utilizing the nonlinear optical effects such as cross-phase modulation (XPM). In some aspects, the manipulation of the refractive index of the waveguide may be applied to waveguides wherein the local oscillator light is guided. This may result in effects similar to manipulating the amplitudes, frequencies and phases of the LO. In other aspects, the manipulation of the refractive index of the waveguide may be applied to waveguides wherein the signal light is guided.

[0225] Multiplexing in the electrical domain may include the manipulation of the electrical responses or properties of the components of the detection units in the coherent detection array, such as the responsivities of the photodetectors. Multiplexing based on the responsivities of the photodetectors may be enabled by controlling the amplitude, frequency and phase of the voltage applied to the photodetector(s) at each detection unit or groups of detection units of the detection array. Photodetector with the responsivity changeable by the applied voltage may include self-mixing detector as described in Non-Patent Document [William C. Ruff, John D. Bruno, Stephen W. Kennerly, Ken Ritter, Paul H. Shen, Barry L. Stann, Michael R. Stead, Zoltan G. Sztankay, Mary S. Tobin, "Self-mixing detector candidates for an FM/cw ladar architecture," Proc. SPIE 4035, Laser Radar Technology and Applications V, (5 September 2000)]. The modulated photocurrents from different coherent detection units may be multiplexed to form multiplexed electrical readout signals. The amplitudes, frequencies and phases of the voltage applied to the photodetectors of the detection units may also be temporally modulated so that the multiplexed electrical readout signals may vary in time accordingly.

[0226] Any combination of time-division multiplexing schemes, space-division multiplexing schemes, the multiplexing schemes utilizing the LO, the multiplexing schemes exploiting the waveguides of the detection array, and the multiplexing schemes exploiting the responsivity of the photodetector may be applied concurrently or not concurrently to the coherent detection array. Signal post-processing may be applied to the multiplexed electrical readout signals to extract information regarding the signal light measured at the detection units.

[0227] FIG. 28 illustrates a conceptual setup of a coherent detection apparatus comprising a coherent detection array 91, an optical input circuit 92, an electrical multiplexing circuit 93, and an electrical readout circuit 94, wherein any combination of time-division multiplexing schemes, space-division multiplexing schemes, the multiplexing schemes utilizing the LO, the multiplexing schemes exploiting the waveguides of the detection array, and the multiplexing schemes exploiting the responsivity of the photodetector may be applied.

[0228] For the embodiments of the coherent detection array of the present invention illustrated in FIGS. 2, 3, 6, 7, 8, 9, 14, 15, 16, 17, 18, 19, 20, 21, 24, 25, 26 and 27, the electric currents at the output ends of the column-readout wirings on column n of the coherent detection array are proportional to

$$I_{(n)}(t) = \sum_{m=1}^M R_{(m,n)}(t) [P_{0(m,n)} + \langle E_{LO,in(m)}(t) E_{Sig,in(m,n)}(t) \rangle], \quad (1)$$

wherein t denotes time, $E_{LO,in(m)}(t)$ is the electric field of the LO light on row m , $E_{Sig,in(m,n)}(t)$ is the electric field of the signal light coupled to the free-space-to-waveguide coupler at the coherent detection unit on row m and column n , and $R_{(m,n)}(t)$ is the responsivity of the corresponding photodetector. The indices $m = 1, 2, \dots, M$ and $n = 1, 2, \dots, N$, where M and N denote respectively the numbers of rows and columns of the coherent detection array. The quantity $P_{0(m,n)}$ is a direct component proportional to the average intensities of the signal light and the local oscillator light at the coherent detection unit on row m and column n . For the embodiments of the coherent detection array illustrated in FIGS. 2, 3, 6, 7, 8, 9, 14, 15, 16, 17, 18, 19, 20 and 21, $M = 3$ and $N = 4$, whereas $M = 2$ and $N = 3$ for the illustrations in FIGS. 24, 25, 26 and 27. For the embodiments of the coherent detection array illustrated in FIGS. 14, 15, 16, 17, 18, 19, 20, 21, 24, 25, 26 and 27, the electric fields of the local oscillator light $E_{LO,in(m)}(t)$ and the signal light $E_{Sig,in(m,n)}(t)$ in Equation (1) may further be indexed by the polarization. The photodetector responsivity $R_{(m,n)}(t)$ may also be indexed by the detector label for the coherent detection unit with more than one photodetector implemented. The photodetector responsivity $R_{(m,n)}(t)$ may be determined through calibrations of the coherent detection array. A noise component that may be present has been neglected in Equation (1) for the sake of simplicity.

[0229] Embodiments of the multiplexing methods leveraging the extra degrees of freedom in the optical and electrical domain for coherent detection as manifested by the manipulation of the LO and photodetector responsivity will be described below.

Multiplexing Methods by Local Oscillator

[0230] In the following, the principles and embodiments of the multiplexing methods leveraging the designs of the coherent detection array of the present invention and exploiting the local oscillator are described.

[0231] In some aspects, multiplexing for signal readout may be realized by manipulating the LO. In those circumstances, the photodetector responsivity $R_{(m,n)}$ may be treated as

independent of or slowly varying in time. The cross component $\langle E_{\text{LO},\text{in}(m)}(t)E_{\text{Sig},\text{in}(m,n)}(t) \rangle$ of the electric current in Equation (1) may then be extracted by suppressing the direct component of the electric current by an appropriate filter if the direct component is slowly varying compared to the cross component, or by taking a difference between the photocurrents by the photodetectors for the cases of the embodiments of the coherent detection array illustrated in FIGS. 2, 3, 24, 25, 26 and 27 wherein balanced configurations may be implemented. The cross components of the electric currents at the output ends of the column-readout wirings on column n of the coherent detection array are then proportional to

$$I_{\text{ac}(n)}(t) = \sum_{m=1}^M R_{(m,n)} \langle E_{\text{LO},\text{in}(m)}(t)E_{\text{Sig},\text{in}(m,n)}(t) \rangle. \quad (2)$$

Equation (2) manifests that, by introducing local oscillator light $E_{\text{LO},\text{in}(m)}$ with a nonzero amplitude in the row-encoding waveguide on row m while setting the local oscillator light in other rows to zero, the cross components of the electric currents at the output ends of the column-readout wirings on column n are proportional to $\langle E_{\text{LO},\text{in}(m)}(t)E_{\text{Sig},\text{in}(m,n)}(t) \rangle$. Consequently, the local oscillator light may be used to select a particular row of the coherent detection array.

[0232] In some aspects, the described methods for signal multiplexing may be implemented in view of Equation (2) by controlling the local oscillator light to select the rows of the coherent detection array one-by-one sequentially or non-sequentially, so that all the rows may be readout in M steps. In other aspects, multiplexing may be implemented by introducing nonzero local oscillator light simultaneously into subsets of rows of the coherent detection array. Additionally, the local oscillator light may be introduced into different subsets of rows of the coherent detection array at different times. Also, the electrical signals at the output ends of the column-readout wirings on different columns of the detection array may be multiplexed using existing common readout methods for output to external circuits. Furthermore, signal post-processing may be applied to extract the information of the signal light.

[0233] Two other exemplars of the embodiments of the multiplexing methods based on the frequency or amplitude of the LO are described in the following. It is understood that the exemplars are non-exhaustive. In some aspects, other multiplexing schemes may be used to exploit any combination of the amplitude, frequency and phase of the local oscillator light.

Multiplexing Method Based on Frequency Offsets of the Local Oscillator

[0234] In the following, an embodiment of the multiplexing method that exploits the frequency of the local oscillator is described.

[0235] In some aspects, local oscillator light with different optical frequencies may be introduced into different rows of the coherent detection array to multiplex the electric currents in the column-readout wirings according to Equation (2). In this respect, the different terms of the sum in Equation (2) may exhibit different beating frequencies wherein signal processing may be applied to de-multiplex the information of different rows.

[0236] An application of the multiplexing method utilizing different frequencies of the LO to coherent detection is to extend FMCW-LIDAR (see Non-Patent Document [A. Dieckmann, “FMCW-LIDAR with tunable twin-guide laser diode,” Electronics Letters 30, 308-309 (1994)]) to achieve simultaneous full-field 3D FMCW-LIDAR. Taking as an exemplar of applying the 3D FMCW-LIDAR on a target using a full-field-illuminating probe laser with a linear frequency chirped at the central frequency f_0 with a frequency tuning range B for a sweeping period T_s . With the coherent detection array, when the local oscillator light $E_{\text{LO},in\ m}$ in row m is frequency-offset from f_0 by Ω_m with $m = 1, \dots, M$, the cross components of the FMCW photocurrents at the output ends of the column-readout wirings of column n are proportional to

$$I_{\text{ac}(n)}^{\text{FMCW}}(t) = \sum_{m=1}^M R_{(m,n)} |E_{\text{LO},in(m)}| |E_{\text{Sig},in(m,n)}| \cos \left(2\pi \left(\frac{\tau_{mn}}{T_s} B + \Omega_m \right) t + \theta_{mn} \right), \quad (3)$$

with the phase factor

$$\theta_{mn} = 2\pi\tau_{mn} \left(f_0 - \frac{\tau_{mn}}{T_s} B \right) + \Delta\Phi_{mn}(t, \tau),$$

where τ_{mn} is the round-trip time for the probe beam transmitting to and reflecting from the target and travelling to the coherent detection unit at row m and column n . The phase difference $\Delta\Phi_{mn}(t, \tau)$ contains the phase noise of the laser. By setting the frequency offsets Ω_m at sufficiently large values, such as but not limited to $\Omega_m = m \frac{\tau_c}{T_s} B$ where τ_c is the coherence time of the probe laser, so that the FMCW photocurrent components from different row m are shifted to distinct frequency bands, the round-trip times τ_{mn} for all m may be uniquely determined from the

frequency spectra of the FMCW photocurrents. Consequently, the frequencies of the local oscillator fields may be exploited to select subsets of rows of the coherent detection array and demultiplex the information of the signals of the rows.

[0237] FIGS. 29A and 29B schematically depict examples of the spectra of the cross components of the FMCW photocurrents without and with the LO frequency offsets respectively. Since the signals of interest are purely real, only the positive frequencies are shown. FIG. 29A shows an example for the case of the spectrum without the frequency offsets, which corresponds to Equation (3) with $\Omega_m = 0$. Consider an example of the photocurrent composing of signals from three detection units in a column (e.g., detection units 1, 2, 3 at rows 1, 2 and 3 of column 1), wherein detection units 1 and 3 detect the signals from probe beams with round-trip times both equal to $\Delta T_s/B$, i.e. $\tau_{11} = \tau_{31} = \Delta T_s/B$, and detection unit 2 detects the signal from a probe beam with a round-trip time $\tau_{21} = \Delta' T_s/B$. Assume that the signal at the three detection units have the same amplitude and phase for illustrative purposes. Since the round-trip times at detection units 1 and 3 are the same, the photocurrents from detection units 1 and 3 add up. Thus, the amplitude of the photocurrent at the frequency Δ is twice of that at the frequency Δ' as depicted in FIG. 29A. In addition, since the photocurrents from the three detection units are summed, there is no way to distinguish their respective contributions from the combined photocurrent. FIG. 29B shows the case of the spectrum when frequency offsets Ω_m with $m = 1, 2, 3$ are applied to the LO at the detection units 1, 2 and 3 respectively. The frequencies of the photocurrents from the three detection units may then be separated in distinct bands, so that the contributions from the detection units, as well as the round-trip time information of the probe beams at the detection units, may be determined individually.

Multiplexing Method Based on Compressed Sensing

[0238] In the following, an embodiment of the multiplexing method that exploits the amplitude of the local oscillator is described.

[0239] In some aspects, the selections of the subsets of rows of the coherent detection array and the signal post-processing may be based on the method of compressed sensing (CS) (see Non-Patent Document [D. L. Donoho, "Compressed sensing," IEEE Transactions on Information

Theory 52, 1289 (2000)]). To illustrate the principle of the multiplexing method, the incident signal light is taken to be a continuous wave (CW) signal in the following description, though in general the method works for any incident signal light.

[0240] In some implementations of the CS method, the incident signal light may be measured K times, wherein each measurement may last for a duration T_k with $k = 1, 2, \dots, K$. The cross components of the electric currents at the output ends of the column-readout wirings on column n of the coherent detection array at the k th measurement according to Equation (2) are proportional to

$$I_{ac(n)}^{(k)}(t_k) = \sum_{m=1}^M R_{(m,n)} |E_{LO,in(m)}^{(k)}| |E_{Sig,in(m,n)}| \cos(2\pi\Delta_{mn}t_k + \theta'_{mn}) , \quad (4)$$

where $E_{LO,in(m)}^{(k)}(t_k)$ is the local oscillator light at the row-encoding waveguide in row m in the k th measurement, $|E_{LO,in(m)}^{(k)}|$ and $|E_{Sig,in(m,n)}|$ are the magnitudes of $E_{LO,in(m)}^{(k)}(t_k)$ and $E_{Sig,in(m,n)}(t_k)$ respectively, Δ_{mn} is the beat frequency of the signal light with the local oscillator light at the detection unit on row m and column n , and θ'_{mn} is the corresponding phase shift. The time t_k falls within the duration T_k of the k th measurement. Consider the situation when θ'_{mn} is deterministic for illustrative purposes, i.e., the phase variations in Equation (2) are neglected. In the Fourier domain, Equation (4) may be written in a matrix form: $\mathbf{I}_{ac(n)} = \mathbf{E}_{LO}\mathbf{x}_n$, wherein the elements of the vector $\mathbf{x}_n$ are $|E_{Sig,in(m,n)}| [e^{i\theta'_{mn}}\delta(f - \Delta_{mn}) + e^{-i\theta'_{mn}}\delta(f + \Delta_{mn})]$ with $\delta(f)$ being the delta function in the Fourier domain. Here, for any column n , $\mathbf{I}_{ac(n)}$ is a vector of length K , $\mathbf{x}_n$ is a vector of length M , and $\mathbf{E}_{LO}$ is a matrix of size $K \times M$. The local oscillator light together with the constants $R_{(m,n)}$, as represented by $\mathbf{E}_{LO} = R_{(m,n)} |E_{LO,in(m)}^{(k)}|$, thus plays the role of the sensing matrix in CS. When the unknown signal vector $\mathbf{x}_n$ is sparse according to the CS theory, it may be recovered efficiently through a signal reconstruction algorithm.

Multiplexing Methods by Photodetector

[0241] In the following, the principles and an embodiment of the multiplexing methods leveraging the designs of the coherent detection array of the present invention and exploiting the properties of the photodetector are described.

[0242] In some aspects, multiplexing through the manipulation of the properties of the photodetector may be performed in the embodiments of the coherent detection arrays illustrated in FIGS. 3, 7, 9, 15, 17, 19, 21, 25 and 27 wherein row-encoding wirings are implemented. For those circumstances, the responsivity of the photodetector may be written in the form $R_{(m,n)}f_{(m)}(t)$ so that the temporal dependence of the responsivity is the same across a row of the detection units of the coherent detection array and the factor $R_{(m,n)}$ accounts for the variations of the responsivities among different photodetectors of the different detection units. The function $f_{(m)}(t)$ may be temporally controlled by changing the voltage applied to the photodetectors on row m of the detection array. According to Equation (1), the electric currents at the output ends of the column-readout wirings on column n of the coherent detection array may then be written as

$$I_{(n)}(t) = \sum_{m=1}^M R_{(m,n)}f_{(m)}(t)[P_{0(m,n)} + \langle E_{\text{LO},\text{in}(m)}(t)E_{\text{Sig},\text{in}(m,n)}(t) \rangle]. \quad (5)$$

According to Equation (5), time-division multiplexing methods may be implemented to select the photodetector output on row m by setting a nonzero value to $f_{(m)}(t)$ while switching off the other rows.

[0243] In some aspects, the function $f_{(m)}(t)$ may be exploited to provide frequency offsets to multiplex the output signal in a manner similar to the multiplexing method based on the frequency offsets of the local oscillator as manifested in Equation (3). As an illustration, consider the application in the simultaneous full-field 3D FMCW-LIDAR with the local oscillator frequency offsets set to zero and the responsivities take the form $f_{(m)}(t) = C_m + A_m \cos 2\pi\Omega_m t$. Then Equation (5) may be written as

$$I_{(n)}^{\text{FMCW}}(t) = I_{(n)}^{\text{base}}(t) + I_{(n)}^{\text{shift}}(t), \quad (6)$$

where the base-band current is given by

$$I_{(n)}^{\text{base}}(t) = \sum_{m=1}^M R_{(m,n)} C_m \left[P_{0(m,n)} + |E_{\text{LO,in}(m)}| |E_{\text{Sig,in}(m,n)}| \cos \left(2\pi \frac{\tau_{mn}}{T_s} B t + \theta_{mn} \right) \right], \quad (7)$$

and the band-shifted current is given by

$$\begin{aligned} I_{(n)}^{\text{shift}}(t) = \sum_{m=1}^M R_{(m,n)} A_m \bigg\{ & P_{0(m,n)} \cos 2\pi \Omega_m t \\ & + \frac{1}{2} |E_{\text{LO,in}(m)}| |E_{\text{Sig,in}(m,n)}| \left[\cos \left(2\pi \left(\frac{\tau_{mn}}{T_s} B + \Omega_m \right) t + \theta_{mn} \right) \right. \\ & \left. + \cos \left(2\pi \left(\frac{\tau_{mn}}{T_s} B - \Omega_m \right) t + \theta_{mn} \right) \right] \bigg\}. \quad (8) \end{aligned}$$

[0244] On one hand, the base-band current in Equation (7) corresponds to the signal component that is unaffected by the multiplexing through the temporal modulations of the responsivities of the photodetectors.

[0245] On the other hand, similar to the situation represented by Equation (3), the summands of the band-shifted current according to Equation (8) at different rows of the detection array are shifted by the modulation frequencies Ω_m of the photodetector responsivities. When the modulation frequencies Ω_m are sufficiently large, the FMCW photocurrent components containing the distance information τ_{mn} with different m may be shifted to distinct frequency bands. Consequently, the frequency-modulation applied to the photodetector responsivity may be exploited to select subsets of rows of the coherent detection array and de-multiplex the information of the signals of the rows, in a manner similar to the multiplexing method by the LO frequency offsets.

[0246] Different from the situation represented by Equation (3), the distance information in the band-shifted current may manifest as two sidebands around the shifted average power term $P_{0(m,n)}$ centered at Ω_m . Therefore, more sophisticated signal post-processing may be needed to extract such information.

[0247] FIGS. 30A-C schematically depict examples of the spectra of the FMCW photocurrents when the photodetector responsivities are modulated sinusoidally. Conditions and parameters the same as that in FIGS. 29A and 29B are considered. Since the signals of interest are purely real, only the positive frequencies are shown. FIG. 30A shows an example for the case of

the spectrum without the modulation, which corresponds to Equation (6) with $A_m = 0$. FIG. 30A is the same as FIG. 29A except that the direct component corresponding to the average power $P_{0(m,n)}$ is present. FIG. 30B shows the case of the spectrum when sinusoidal modulations at frequencies Ω_m with $m = 1, 2, 3$ are applied to the photodetectors at the detection units 1, 2 and 3 respectively. The frequencies of the photocurrents from the three detection units are separated in distinct bands though exhibiting more complicated patterns than FIG. 29B. FIG. 30C shows the situation when the terms containing the average power $P_{0(m,n)}$ in Equations (5), (7) and (8) may be suppressed by taking a difference between the photocurrents by the photodetectors for the cases of the embodiments of the coherent detection array illustrated in FIGS. 2, 3, 24, 25, 26 and 27 wherein balanced configurations may be implemented.

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[0250] A. Dieckmann, "FMCW-LIDAR with tunable twin-guide laser diode," Electronics Letters 30, 308-309 (1994).

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CLAIMS

What is claimed is:

1. A coherent detection array comprising:

a plurality of coherent detection units, each coherent detection unit including:

a free-space-to-waveguide coupler;

a first waveguide for guiding local oscillator light, wherein said first waveguide couples with said free-space-to-waveguide coupler through a first optical coupler; and

one or more photodetectors coupling with and receiving photons from said first optical coupler;

one or more connecting waveguides coupling with said plurality of coherent detection units through a plurality of second optical couplers, wherein each connecting waveguide couples with a first subset or all of said plurality of coherent detection units, said connecting waveguide couples with each coherent detection unit of said first subset or all of said plurality of coherent detection units by coupling with the first waveguide of said coherent detection unit through one of said second optical couplers; and

one or more electrical conducting paths coupling with said plurality of coherent detection units, wherein each electrical conducting path couples with a second subset or all of said plurality of coherent detection units, said electrical conducting path couples with each coherent detection unit of said second subset or all of said plurality of coherent detection units by coupling with one or more of the photodetectors of said coherent detection unit;

whereby:

some or all of said electrical conducting paths manifest as readout channels for multiplexing electrical signals output from the photodetectors with which said readout channels couple.

2. The coherent detection array of claim **1**, wherein:

the free-space-to-waveguide couplers of some or all of said plurality of coherent detection units are polarized-light separating free-space-to-waveguide couplers; and

each of those coherent detection units comprising said polarized-light separating free-space-to-waveguide couplers further comprises:

a second waveguide for guiding local oscillator light, said second waveguide couples with said polarized-light separating free-space-to-waveguide coupler through a third optical coupler; and

one or more photodetectors coupling with and receiving photons from said third optical coupler.

3. The coherent detection array of claim 2, wherein, for each of those coherent detection units comprising said polarized-light separating free-space-to-waveguide couplers, the first waveguide and the second waveguide of said coherent detection unit couple with one of said connecting waveguides through one or more of said second optical couplers.

4. The coherent detection array of claim 2, wherein, for each of those coherent detection units comprising said polarized-light separating free-space-to-waveguide couplers, the first waveguide of said coherent detection unit couples with one of said connecting waveguides through one or more of said second optical couplers, the second waveguide of said coherent detection unit couples with another one of said connecting waveguides through another one or more of said second optical couplers.

5. A coherent detection array comprising:

a plurality of coherent detection units, each coherent detection unit including:

a free-space-to-waveguide coupler;

a first optical coupler coupling with said free-space-to-waveguide coupler; and

one or more photodetectors coupling with and receiving photons from said first optical coupler;

one or more connecting waveguides coupling with said plurality of coherent detection units, wherein each connecting waveguide couples with a first subset or all of said plurality of coherent detection units, said connecting waveguide couples with each coherent detection

unit of said first subset or all of said plurality of coherent detection units by coupling directly with the first optical coupler of said coherent detection unit; and

one or more electrical conducting paths coupling with said plurality of coherent detection units, wherein each electrical conducting path couples with a second subset or all of said plurality of coherent detection units, said electrical conducting path couples with each coherent detection unit of said second subset or all of said plurality of coherent detection units by coupling with one or more of the photodetectors of said coherent detection unit;

whereby:

some or all of said electrical conducting paths manifest as readout channels for multiplexing electrical signals output from the photodetectors with which said readout channels couple.

6. The coherent detection array of claim **5**, wherein:

the free-space-to-waveguide couplers of some or all of said plurality of coherent detection units are polarized-light separating free-space-to-waveguide couplers; and

each of those coherent detection units comprising said polarized-light separating free-space-to-waveguide couplers further comprises:

a second optical coupler coupling with said polarized-light separating free-space-to-waveguide coupler; and

one or more photodetectors coupling with and receiving photons from said second optical coupler.

7. The coherent detection array of claim **6**, wherein, for each of those coherent detection units comprising said polarized-light separating free-space-to-waveguide couplers, the first optical coupler and the second optical coupler of said coherent detection unit couple directly with one of said connecting waveguides.

8. The coherent detection array of claim **6**, wherein, for each of those coherent detection units comprising said polarized-light separating free-space-to-waveguide couplers, the first optical coupler of said coherent detection unit couples directly with one of said connecting waveguides,

the second optical coupler of said coherent detection unit couples directly with another one of said connecting waveguides.

9. The coherent detection array of claim 6, further comprising:

a plurality of third optical couplers;

wherein:

each of those coherent detection units comprising said polarized-light separating free-space-to-waveguide couplers further comprises:

a waveguide coupling with said second optical coupler; and

for each of those coherent detection units comprising said polarized-light separating free-space-to-waveguide couplers, the first optical coupler of said coherent detection unit couples directly with one of said connecting waveguides, the waveguide of said coherent detection unit couples with the same said connecting waveguide through one or more of said third optical couplers.

10. The coherent detection array of claim 6, further comprising:

a plurality of third optical couplers;

wherein:

each of those coherent detection units comprising said polarized-light separating free-space-to-waveguide couplers further comprises:

a waveguide coupling with said second optical coupler; and

for each of those coherent detection units comprising said polarized-light separating free-space-to-waveguide couplers, the first optical coupler of said coherent detection unit couples directly with one of said connecting waveguides, the waveguide of said coherent detection unit couples with another one of said connecting waveguides through one or more of said third optical couplers.

11. A method for optical coherent detection and signal readout with a coherent detection array, the method comprising the steps of:

coupling signal light with a first subset of a plurality of coherent detection units of a coherent detection array, wherein said first subset includes some or all coherent detection units of said plurality of coherent detection units;

introducing one or more local oscillator (LO) signals into a second subset of said plurality of coherent detection units, wherein said second subset includes some or all coherent detection units of said plurality of coherent detection units, said first subset and said second subset overlap to give an intersecting set including at least one coherent detection unit;

registering first information relating to said second subset, said first information includes the positions of the coherent detection units of said second subset, and/or properties, such as amplitudes, frequencies, relative phases, and application times and durations, of said local oscillator signals introduced into said second subset;

performing optical mixing at optical couplers of said plurality of coherent detection units;

detecting optical signals output from said optical couplers of said plurality of coherent detection units by photodetectors of said plurality of coherent detection units to produce electrical signals comprising information of said optical signals;

combining said electrical signals into one or more combined electrical signals for readout, wherein each said combined electrical signal is combined from the electrical signals produced by those photodetectors of said plurality of coherent detection units that are coupled with a common readout channel; and

extracting separately, for each coherent detection unit of said intersecting set of said first subset and said second subset, second information relating to the cross component of the electrical signal of said coherent detection unit from said combined electrical signals by recognizing said second information using said first information relating to said second subset, wherein said cross component is related to the product of the electric fields of the signal light and the local oscillator signal inputting into said coherent detection unit.

12. The method of claim **11**, further comprising the step of filtering the direct components of the electrical signals produced by the photodetectors of said plurality of coherent detection units, said step of filtering the direct components comprises the step of performing high-pass filtering.

13. The method of claim **11**, further comprising the step of filtering the direct components of the electrical signals produced by the photodetectors of said plurality of coherent detection units, said step of filtering the direct components comprises the step of subtracting signals from pairs of photodetectors of some or all coherent detection units of said plurality of coherent detection units wherein a balanced configuration is implemented for each said coherent detection unit of said plurality of coherent detection units.

14. The method of claim **11**, wherein:

said second subset comprises coherent detection units coupling with a first common connecting waveguide, each coherent detection unit of said second subset couples with a readout channel wherein different coherent detection units of said second subset couple with different readout channels; and

said step of extracting said second information is carried out by recognizing that the cross component of the combined electrical signal of each said readout channel is contributed predominantly from only one coherent detection unit of said second subset.

15. The method of claim **14**, further comprising the step of iterating, for a number of times, said steps of introducing LO signals into said second subset, registering first information, performing optical mixing, detecting optical signals, combining electrical signals, and extracting second information, wherein in each iteration said second subset is changed to comprise coherent detection units coupling with a second common connecting waveguide, said second common connecting waveguide is different from said first common connecting waveguide.

16. The method of claim **15**, further comprising, within said step of iterating, the step of changing said first subset to comprise coherent detection units so that said intersecting set of said first subset and said second subset includes at least one coherent detection unit.

17. The method of claim **11**, further comprising the steps of:

partitioning said plurality of coherent detection units of said coherent detection array into a plurality of groups, wherein the coherent detection units of each group couple with a common connecting waveguide;

coupling said coherent detection array with a plurality of readout channels, wherein each readout channel couples with one coherent detection unit from each said group; and

iterating, for a number of times, said steps of introducing LO signals into said second subset, registering first information, performing optical mixing, detecting optical signals, and combining electrical signals, wherein in each iteration said second subset is changed to comprise the coherent detection units of different combinations of said groups, in such a way that the conditions to apply a compressed sensing method are met;

wherein:

said second subset comprises the coherent detection units of one or more said groups;

said step of introducing local oscillator signals into said second subset comprises the step of introducing said local oscillator signals exhibiting some common properties, such as the same frequency, amplitudes following the same distribution, etc., into said second subset;

said step of iterating further comprises the step of recording said combined electrical signals; and

said step of extracting said second information is carried out by applying a signal reconstruction algorithm that corresponds to said compressed sensing method.

18. The method of claim **11**, further comprising the steps of:

partitioning said plurality of coherent detection units of said coherent detection array into a plurality of groups, wherein the coherent detection units of each group couple with a common connecting waveguide; and

coupling each coherent detection unit of said plurality of coherent detection units with one or more readout channels, wherein each of said readout channels couples with one or more

coherent detection units of different said groups, said readout channel does not couple with more than one coherent detection unit from any one said group;

wherein:

said second subset includes the coherent detection units of at least two said groups;

said step of introducing local oscillator signals into said second subset comprises the step of introducing said local oscillator signals with frequencies different from each other by finite frequency offsets into said second subset, wherein one said local oscillator signal is introduced into one said group in said second subset, different said groups in said second subset are introduced with local oscillator signals with different frequency offsets, said frequency offsets are chosen in such a way that, for the coherent detection units belonging to different said groups in said second subset, the electrical signals produced by the photodetectors of these coherent detection units are to be shifted to distinct frequency bands; and

said step of extracting said second information is carried out by recognizing that the cross component of the combined electrical signal of each said readout channel is contributed predominantly from those coherent detection units that belong to different said groups in said second subset.

19. The method of claim **11**, further comprising the step of:

registering third information relating to the positions of the coherent detection units of a third subset of said plurality of coherent detection units, wherein said third subset includes some or all coherent detection units of said plurality of coherent detection units, said first subset, said second subset, and said third subset include at least one common coherent detection unit;

switching on the photodetectors of said third subset by an electrical multiplexing circuit; and

switching off the photodetectors of those coherent detection units of said plurality of coherent detection units not included in said third subset by said electrical multiplexing circuit;

wherein:

said step of extracting said second information is carried out for those coherent detection units of said intersecting set also belonging to said third subset by incorporating additionally said third information.

20. The method of claim **19**, further comprising the steps of:

partitioning the coherent detection units of said third subset into a plurality of groups, wherein the responsivities of the photodetectors of the coherent detection units of each group are modulated in the same way by said electrical multiplexing circuit;

coupling each coherent detection unit of said third subset with one or more readout channels, wherein each of said readout channels couples with one or more coherent detection units of different said groups, said readout channel does not couple with more than one coherent detection unit from any one said group; and

modulating the responsivities of the photodetectors of the coherent detection units of different groups with frequencies differing from each other by finite frequency offsets, said frequency offsets are chosen in such a way that, for those coherent detection units coupling with a common readout channel, the electrical signals produced by the photodetectors of these coherent detection units are shifted to distinct frequency bands;

wherein:

said step of extracting said second information is carried out by recognizing that the cross component of the combined electrical signal of each said readout channel is contributed predominantly from those coherent detection units of said third subset whose photodetectors produce electrical signals that are shifted to different frequency bands; and

said step of extracting said second information is carried out by incorporating fourth information relating to the responsivities of the photodetectors being modulated, said fourth information includes the modulating frequencies and amplitudes of said responsivities.