~~What is claimed is:~~Claims

1. A coherent detection apparatus, comprising:

an array of coherent detection units, each coherent detection unit including:

a free-space-to-waveguide coupler for receiving signal light;

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

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

one or more connecting waveguides optically coupled with said coherent detection units through a plurality of second optical couplers, wherein each connecting waveguide is optically coupled with at least a first subset of said coherent detection units, each coherent detection unit of said first subset of said coherent detection units being optically coupled with a selected one of said connecting waveguides through one of said second optical couplers to the first waveguide of said each coherent detection unit;

one or more electrical conducting paths electrically coupled with said plurality of coherent detection units, wherein each electrical conducting path is electrically coupled with at least a second subset of said coherent detection units, each coherent detection unit of said second subset of said coherent detection units being electrically coupled with a selected one of said electrically conducting paths through said one or more photodetectors of said each coherent detection unit; and

an electrical circuit electrically coupled with said electrical conducting paths;

wherein said electrical conducting paths manifest as readout channels for multiplexing electrical signals output from the photodetectors with which said readout channels couple;

wherein said electrical circuit is configured to extract information relating to a cross component of the multiplexed electrical signals by recognizing that the cross component of the multiplexed electrical signal of said readout channels is contributed

predominantly from a group of coherent detection units in a selected one of said readout channels,

wherein said cross component is related to a product of electric fields of the signal light and the local oscillator signals transmitted into said coherent detection units.

2. The coherent detection apparatus of claim 1, wherein:

the free-space-to-waveguide couplers of at least some of said coherent detection units are polarized-light separating free-space-to-waveguide couplers; and

each of said 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 being optically coupled with said polarized-light separating free-space-to-waveguide coupler through a third optical coupler; and

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

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

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

5. A coherent detection apparatus, comprising:

an array of coherent detection units, each coherent detection unit including:

a free-space-to-waveguide coupler for receiving signal light;

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

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

one or more connecting waveguides optically coupled with said coherent detection units, wherein each connecting waveguide is optically coupled with at least a first subset of said coherent detection units, each coherent detection unit of said first subset of coherent detection units being optically coupled directly with the first optical coupler of said each coherent detection unit;

one or more electrical conducting paths electrically coupled with said plurality of coherent detection units, wherein each electrical conducting path is electrically coupled with at least a second subset of said coherent detection units, each coherent detection unit of said second subset of said coherent detection units being electrically coupled with a selected one of said electrically conducting paths through said one or more photodetectors of said each coherent detection unit; and

an electrical circuit electrically coupled with said electrical conducting paths;

wherein said electrical conducting paths manifest as readout channels for multiplexing electrical signals output from the photodetectors with which said readout channels couple, and

wherein said electrical circuit is configured to extract information relating to a cross component of the multiplexed electrical signals by recognizing that the cross component of the multiplexed electrical signal of said readout channels is contributed predominantly from a group of coherent detection units in a selected one of said readout channels,

wherein said cross component is related to a product of electric fields of the signal light and the local oscillator signals transmitted into said coherent detection units.

6. The coherent detection apparatus of claim 5, wherein:

the free-space-to-waveguide couplers of at least some of said coherent detection units are polarized-light separating free-space-to-waveguide couplers; and

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

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

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

7. The coherent detection apparatus of claim 6, wherein, for each of the coherent detection units comprising said polarized-light separating free-space-to-waveguide couplers, the first optical coupler and the second optical coupler are optically coupled directly with one of said connecting waveguides.

8. The coherent detection apparatus of claim 6, wherein, for each of the coherent detection units comprising said polarized-light separating free-space-to-waveguide couplers, the first optical coupler is optically coupled directly with one of said connecting waveguides, and the second optical coupler is optically coupled directly with another one of said connecting waveguides.

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

a plurality of third optical couplers;

wherein:

each of the coherent detection units comprising said polarized-light separating free-spaceto-waveguide couplers further comprises:

a waveguide optically coupled with said second optical coupler; and

for each of the coherent detection units comprising said polarized-light separating free-space-to-waveguide couplers, the first optical coupler is optically coupled directly with one of said connecting waveguides, the waveguide of said each

of the coherent detection units being optically coupled with the same one of said connecting waveguides through one or more of said third optical couplers.

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

a plurality of third optical couplers;

wherein:

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

a waveguide optically coupled with said second optical coupler; and

for each of the coherent detection units comprising said polarized-light separating free-space-to-waveguide couplers, the first optical coupler is optically coupled directly with one of said connecting waveguides, the waveguide of said each of the coherent detection units is optically coupled 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 using a coherent detection device, the method comprising the steps of:

coupling signal light with a first subset of coherent detection units of the coherent detection device;

introducing one or more local oscillator signals into a second subset of said coherent detection units, coherent detection units in said second subset being optically coupled with a first common connecting waveguide for transmitting the local oscillator signals and each coherent detection unit in said second subset being electrically coupled to a different readout channel, said first subset overlapping with said second subset to define a first intersecting set including at least one of said coherent detection units;

registering first information relating to said second subset in the coherent detection device, said first information including positions of the coherent detection units in said second subset and physical properties of said local oscillator signals introduced into said second subset, said physical properties including at least one of

amplitudes, frequencies, relative phases, and application times and durations of said local oscillator signals;

performing optical mixing of said signal light and said local oscillator signals at optical couplers of said coherent detection units;

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

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

extracting separately, for each coherent detection unit of said first intersecting set, second information relating to a cross component of the electrical signal of said each 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 a product of the electric fields of the signal light and the local oscillator signals transmitted into said each coherent detection unit, and

wherein recognizing said second information comprises recognizing that the cross component of the combined electrical signal of said common readout channel is contributed predominantly from only one coherent detection unit in said second subset.

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 coherent detection units using 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 coherent detection units by subtracting signals from pairs of photodetectors of at least some of

said coherent detection units, wherein a balanced configuration is implemented for each of said coherent detection units.

~~15~~14. The method of claim 11, further comprising the step of iterating, for a number of times, said steps of introducing said local oscillator signals into said second subset, registering said first information, performing said optical mixing, detecting said mixed optical signals, combining said electrical signals, and extracting said second information, wherein in each iteration said second subset is changed to comprise coherent detection units that are optically coupled with a second common connecting waveguide, said second common connecting waveguide being different from said first common connecting waveguide.

~~16~~15. The method of claim ~~15~~14, 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~~16. The method of claim 11, further comprising the steps of:

introducing one or more local oscillator signals into a group of third subsets of said coherent detection units, wherein the coherent detection units in each said third subset are optically coupled with a common connecting waveguide and each coherent detection unit in each said third subset is electrically coupled to a different readout channel, with said second subset being one of said third subsets and a second intersecting set being defined by said first subset overlapping with a union of said third subsets;

registering third information relating to said third subsets in the coherent detection device, said third information including positions of the coherent detection units in said third subsets and physical properties of said local oscillator signals introduced into said third subsets, said physical properties including at least one of

amplitudes, frequencies, relative phases, and application times and durations of said local oscillator signals, with said third information including said first information;

coupling said coherent detection units with a plurality of common readout channels, wherein each said common readout channel is electrically coupled with no more than one coherent detection unit from each of said third subsets; and

iterating, for a number of times, said steps of introducing said local oscillator signals into said third subsets, registering said third information, performing said optical mixing, detecting said optical signals, and combining said electrical signals, wherein in each iteration said group of said third subsets are changed to a different group of said third subsets comprising different combinations of said coherent detection units that are optically coupled with common connecting waveguides, in such a way that the conditions to apply a compressed sensing method are met;

wherein:

said step of introducing said local oscillator signals into said group of said third subsets comprises the step of introducing said local oscillator signals exhibiting some common physical properties into said group of said third subsets, said common physical properties including at least one of the same frequency and amplitudes following the same distribution;

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

said step of extracting said second information for said first intersecting set and said second intersecting set is carried out by additionally incorporating said third information and by applying a signal reconstruction algorithm that corresponds to said compressed sensing method, wherein recognizing said second information comprises recognizing that the cross component of the combined electrical signals of each of said common readout channels is contributed predominantly from no more than one coherent detection unit in each of said third subsets.

~~18~~17. The method of claim 11, further comprising the steps of:

introducing one or more local oscillator signals into a group of third subsets of said coherent detection units, wherein the coherent detection units in each said third subset are optically coupled with a common connecting waveguide and each coherent detection unit in each said third subset is electrically coupled to a different readout channel, with said second subset being one of said third subsets and a second intersecting set being defined by said first subset overlapping with a union of said third subsets;

registering third information relating to said third subsets in the coherent detection device, said third information including positions of the coherent detection units in said third subsets and physical properties of said local oscillator signals introduced into said third subsets, said physical properties including at least one of amplitudes, frequencies, relative phases, and application times and durations of said local oscillator signals, with said third information including said first information; and

coupling said coherent detection units with a plurality of common readout channels, wherein each each common readout channel is electrically coupled with no more than one coherent detection unit from each of said third subsets;

wherein:

said group includes at least two said third subsets; and

said step of introducing said local oscillator signals into said third subsets comprises the step of introducing said local oscillator signals with frequencies different from each other by finite frequency offsets into said third subsets,

wherein one of said local oscillator signals is introduced into one of said third subsets, and different ones of said third subsets are introduced with local oscillator signals with different frequency offsets, said frequency offsets being chosen in such a way that, for the coherent detection units belonging to different ones of said third subsets, 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 for said first intersecting set and said second intersecting set is carried out by additionally incorporating said third

information and by recognizing that the cross component of the combined electrical signals of each of said common readout channels is contributed predominantly from no more than one coherent detection unit in each of said third subsets.

~~19~~18. The method of claim 11, further comprising the step of:

introducing one or more local oscillator signals into a group of third subsets of said coherent detection units, wherein the coherent detection units in each said third subset are optically coupled with a common connecting waveguide and each coherent detection unit in each said third subset is electrically coupled to a different readout channel, with said second subset being one of said third subsets and a second intersecting set being defined by said first subset overlapping with a union of said third subsets;

registering third information relating to said third subsets in the coherent detection device, said third information including positions of the coherent detection units in said third subsets and physical properties of said local oscillator signals introduced into said third subsets, said physical properties including at least one of amplitudes, frequencies, relative phases, and application times and durations of said local oscillator signals, with said third information including said first information;

coupling said coherent detection units with a plurality of common readout channels, wherein each each common readout channel is electrically coupled with no more than one coherent detection unit from each of said third subsets;

registering fourth information relating to positions of a fourth subset of said coherent detection units, wherein said fourth subset includes at least some of said coherent detection units, and wherein said first subset, said third subsets, and said fourth subset include at least a common coherent detection unit;

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

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

wherein:

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

~~20~~19. The method of claim ~~19~~18, further comprising the steps of:

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

electrically coupling each coherent detection unit in said fourth subset with one or more readout channels, wherein each of said readout channels is electrically coupled with one or more coherent detection units of different ones of said groups, and without being coupled with more than one coherent detection unit from any one of said groups; 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 being 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 signals of each of said readout channels is contributed predominantly from those coherent detection units of said fourth 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 fifth information relating to the responsivities of the photodetectors being modulated, said fifth information including the modulating frequencies and amplitudes of said

responsivities.

~~21~~20. The coherent detection apparatus of claim 1, wherein, if said group of coherent detection units comprises more than one coherent detection unit, each coherent detection unit of said group contributes to said cross component with signal features that permit the contribution of each said coherent detection unit to be uniquely identified from said cross component.

~~22~~21. The coherent detection apparatus of claim 5, wherein, if said group of coherent detection units comprises more than one coherent detection unit, each coherent detection unit of said group contributes to said cross component with signal features that permit the contribution of each said coherent detection unit to be uniquely identified from said cross component.

22. A method of optical coherent detection, comprising:

receiving an input light signal from free space using a first subset of coherent detection units of a coherent detection array; introducing a local oscillator (LO) signal through an optical waveguide to a second subset of the coherent detection units, wherein the second subset overlaps with the first subset; optically mixing, in individual overlapping ones of the coherent detection units in the first and second subsets, the input light signal and the LO signal by an optical coupler to generate an output light signal from the optical coupler;

converting, in individual ones of the coherent detection units in a third subset of the coherent detection units, the output light signal to an output electrical signal by a photodetector, wherein the third subset overlaps with the first and second subsets; outputting, through a readout channel, an electrical readout signal based on output electrical signals respectively generated from coherent detection units that are electrically connected to the readout channel in the third subset; and

extracting signal information from a cross component of the electrical readout signal based on detection unit information of an overlapping one of the coherent detection units in the first, second, and third subsets, the signal information being associated with the input light signal received by said overlapping one of the coherent detection units.

23. The method of claim 22, wherein the cross component is related to a product of an electric field of the input light signal and an electric field of the LO signal.

24. The method of claim 22, wherein the detection unit information comprises information related to positions of the coherent detection units of the second subset to which the LO signal is introduced.

25. The method of claim 24, wherein the detection unit information further comprises information related to at least one of an amplitude, a frequency, a relative phase, and application time and duration of the LO signal.

26. The method of claim 22, wherein the detection unit information comprises information related to positions of the coherent detection units of the third subset.

27. The method of claim 22, further comprising filtering out a direct component of the output electrical signal to obtain the cross component using a high-pass filter.

28. The method of claim 22, after optically mixing the input light signal and the LO signal, further comprising splitting the output light signal into a first output light signal and a second output light signal in said individual overlapping ones of the coherent detection units in the first and second subsets; and wherein converting the output light signal comprises: converting the first output light signal to a first output electrical signal by a first photodetector in said individual ones of the coherent detection units in the third subset; and converting the second output light signal to

a second output electrical signal by a second photodetector in said individual ones of the coherent detection units in the third subset.

29. The method of claim 28, after converting the first and second output light signals respectively to the first and second output electrical signals, further comprising taking a difference of the first and second output electrical signals to give rise to a differential output electrical signal in said individual ones of the coherent detection units in the third subset; and wherein outputting the electrical readout signal based on differential output electrical signals respectively generated from the coherent detection units that are electrically connected to the readout channel in the third subset.

30. The method of claim 28, wherein outputting the readout electrical signal comprises: outputting, through a first readout channel, a first electrical readout signal based on the first output electrical signals respectively generated from the coherent detection units that are electrically connected to the first readout channel in the third subset; and outputting, through a second readout channel, a second electrical readout signal based on the second output electrical signals respectively generated from the coherent detection units that are electrically connected to the second readout channel in the third subset; and wherein extracting the signal information associated with the input light signal comprises taking a difference of the first and second electrical readout signals.

31. The method of claim 22, wherein converting the output light signal to the output electrical signal comprises shifting a frequency of the output electrical signal.

32. The method of claim 31, wherein shifting the frequency of the output electrical signal comprises modulating responsivities of the photodetectors in the third set of

the coherent detection units by a finite frequency offset, such that the output electrical signal generated by the photodetector in the third subset is shifted to a distinct frequency band.

33. A coherent detection apparatus, comprising:

a coherent detection array including a plurality of coherent detection units to receive an input light signal from free space;

a plurality of encoding waveguides, each being optically coupled to a first subset of the coherent detection units; a plurality of readout channels, each being electrically connected to a second subset of the coherent detection units;

an optical input circuit to introduce a local oscillator (LO) signal through one of the encoding waveguides to the corresponding first subset of the coherent detection units, the LO signal and the input light signal being optically mixed and converted into an output electrical signal in individual ones of the coherent detection units in the first subset; and

a readout circuit electrically connected to the readout channels;

wherein the readout circuit is configured to: receive an electrical readout signal from the readout channels; and extract signal information from a cross component of the electrical readout signal based on detection unit information of an overlapping one of the coherent detection units in the first and second subsets, the signal information being associated with the input light signal received by said overlapping one of the coherent detection units.

34. The apparatus of claim 33, wherein the electrical readout signal is based on output electrical signals respectively generated from the coherent detection units in the second subset.

35. The apparatus of claim 33, wherein the cross component is related to a product of an electric field of the input light signal and an electric field of the LO signal.

36. The apparatus of claim 33, wherein the detection unit information comprises information related to positions of the coherent detection units of the first subset to which the LO signal is introduced.

37. The apparatus of claim 36, wherein the detection unit information further comprises information related to at least one of an amplitude, a frequency, a relative phase, and application time and duration of the LO signal.

38. The apparatus of claim 33, wherein individual ones of the coherent detection units comprise a high-pass filter to filter out a direct component of the output electrical signal.

39. The apparatus of claim 33, wherein individual ones of the coherent detection units comprise: an optical coupler to mix the input light signal and the LO signal and to split the mixed light signal into a first output light signal and a second output light signal; and first and second photodetectors to convert the first and second output light signals respectively into first and second output electrical signals.

40. The apparatus of claim 39, wherein a difference of the first and second output electrical signals is taken to give rise to a differential output electrical signal; and wherein the readout circuit is configured to receive the electrical readout signal based on differential output electrical signals respectively generated from the coherent detection units in the second subset.

41. The apparatus of claim 39, wherein individual ones of the readout channels comprise: a first readout channel electrically connected to the coherent detection units in the second subset; and a second readout channel electrically connected to the coherent detection units in the second subset; and wherein the readout circuit is configured to: receive first and second electrical readout signals respectively from the

first and second readout channels, the first and second electrical readout signals being respectively based on the first and second output electrical signals generated from the coherent detection units in the second subset; and extract the signal information associated with the input light signal by taking a difference of the first and second electrical readout signals.

42. The apparatus of claim 33, further comprising a plurality of encoding channels, each being electrically connected to a third subset of the coherent detection units; and wherein the readout circuit is configured to: receive an electrical readout signal from the readout channels; and extract signal information from a cross component of the electrical readout signal based on detection unit information of an overlapping one of the coherent detection units in the first, second, and third subsets, the signal information being associated with the input light signal received by said overlapping one of the coherent detection units.

43. The apparatus of claim 42, wherein the detection unit information comprises information related to positions of the coherent detection units of the third subset.

44. The apparatus of claim 42, wherein the photodetectors in one or more of the third subsets of the coherent detection units are switched on through the corresponding encoding channel of the third subset, and wherein the photodetectors in other one or more of the third subsets of the coherent detection units are switched off through the corresponding encoding channel of the third subset.

45. The apparatus of claim 44, wherein the electrical readout signal is based on output electrical signals respectively generated from the overlapping coherent detection units in the second and third subsets, wherein the photodetectors of the third subset are switched on.

46. The apparatus of claim 42, wherein responsivities of the photodetectors of the coherent detection units in the third subset are modulated by a finite frequency offset, such that the output electrical signals generated by the coherent detection units are shifted to a distinct frequency band.