CLAIMS

What is claimed is:

1. A photonic circuit comprising:

a front-end optical splitter configured to split carrier light with uniform power coupling ratios into a plurality of optical carrier signals;

a plurality of first optical modulator cells configured to modulate the plurality of optical carrier signals in accordance with components of a first vector to generate a plurality of first modulated optical signals;

multiple sets of second optical modulator cells, each set associated with a corresponding one of multiple second vectors and comprising a plurality of second optical modulator cells configured to modulate the plurality of first modulated optical signals in accordance with components of that second vector to generate a plurality of second modulated optical signals associated with that second vector;

a plurality of waveguide structures each configured to route a corresponding one of the plurality of first modulated optical signals to corresponding second optical modulator cells of the multiple sets of second optical modulator cells; and

multiple back-end optical combiners each associated with a corresponding one of the multiple second vectors and the associated set of second optical modulator cells and configured to coherently combine the plurality of second modulated optical signals associated with that second vector with uniform power coupling ratios into an optical output signal that represents a scalar product between the first vector and the second vector, wherein the front-end splitter or each of the multiple back-end optical combiners each comprises a symmetric cascade of 3dB couplers.

~~2. The photonic circuit of claim 1, wherein the front-end splitter comprises a symmetric cascade of 3dB couplers.~~

~~3. The photonic circuit of claim 1, wherein each of the multiple back-end optical combiners each comprise a symmetric cascade of 3dB couplers.~~

~~4~~2. The photonic circuit of claim 1, wherein the multiple back-end optical combiners and the plurality of waveguide structures configured to route the first modulated optical signals to the second optical modulator cells form waveguide crossings, the photonic circuit further comprising dummy waveguide crossings in the back-end optical combiners, wherein for each of the sets of second optical modulator cells, the waveguide crossings and the dummy waveguide crossings are balanced in sum across all paths from the plurality of second optical modulator cells of the set to an output of the associated back-end optical combiner.

~~5~~3. The photonic circuit of claim ~~4~~2, further comprising dummy waveguide crossings in the waveguide structures configured to route the first modulated optical signals to the second optical modulator cells, wherein the waveguide crossings and the dummy waveguide crossings are further balanced in sum across all back-end optical combiners.

~~6~~4. The photonic circuit of claim ~~4~~2, wherein the dummy waveguide crossings are spatially clustered.

~~7~~5. A photonic circuit comprising:

a front-end optical splitter configured to split carrier light with uniform power coupling ratios into a plurality of optical carrier signals;

a plurality of first optical modulator cells configured to modulate the plurality of optical carrier signals in accordance with components of a first vector to generate a plurality of first modulated optical signals;

multiple sets of second optical modulator cells, each set associated with a corresponding one of multiple second vectors and comprising a plurality of second optical modulator cells configured to modulate the plurality of first modulated optical signals in accordance with components of that second vector to generate a plurality of second modulated optical signals associated with that second vector;

a plurality of waveguide structures each configured to route a corresponding one of the plurality of first modulated optical signals to

corresponding second optical modulator cells of the multiple sets of second optical modulator cells; and

multiple back-end optical combiners each associated with a corresponding one of the multiple second vectors and the associated set of second optical modulator cells and configured to coherently combine the plurality of second modulated optical signals associated with that second vector with uniform power coupling ratios into an optical output signal that represents a scalar product between the first vector and the second vector~~The photonic circuit of claim 1~~, wherein each of the plurality of waveguide structures comprises, arranged along a waveguide, a series of optical couplers that sequentially couple power fractions of the corresponding first modulated optical signal to the corresponding second optical modulator cells of the multiple sets of second optical modulator cells.

~~8~~6. The photonic circuit of claim ~~7~~5, wherein power coupling ratios of the series of optical couplers are configured to balance optical input power across all sets of second optical modulator cells.

~~9~~7. The photonic circuit of claim ~~7~~5, wherein the second optical modulator cells of the plurality of sets are arranged in a rectangular array of rows and columns, the waveguides of the waveguide structures configured to route the first modulated optical signals to the second optical modulator cells being arranged along the rows, and the second optical modulator cells of each set being arranged along a corresponding one of the columns.

~~10~~8. The photonic circuit of claim ~~9~~7, wherein the multiple back-end optical combiners are each configured to coherently combine the plurality of second modulated optical signals at a bottom of the corresponding column, following all waveguide crossings of the back-end optical combiners with the waveguide structures configured to route the first modulated optical signals.

~~11~~9. The photonic circuit of claim ~~9~~7, wherein the multiple back-end optical combiners are each configured to combine pairs of the second modulated optical signals in between the corresponding waveguides of the waveguide structures

configured to route the first modulated optical signals, preceding waveguide crossings of the back-end optical combiner with the waveguide structures.

~~12~~10. The photonic circuit of claim 1, wherein the second optical modulator cells comprise optical amplitude modulators collectively configurable to implement any positive real-valued matrix.

~~13~~11. The photonic circuit of claim ~~12~~10, wherein the second optical modulator cells further comprise optical phase modulators collectively configurable, in conjunction with the optical amplitude modulators, to implement any real-valued or complex-valued matrix.

~~14~~12. The photonic circuit of claim 1, wherein total active insertion losses at outputs of the multiple back-end optical combiners scale linearly with a size of the first and second vectors.

~~15~~13. The photonic circuit of claim 1, further comprising, at outputs of the multiple back-end optical combiners, optical amplifiers or attenuators collectively configurable to restore a fidelity of the photonic circuits to 100%.

~~16~~14. A photonic circuit comprising:

a front-end optical splitter configured to split carrier light with uniform power coupling ratios into a plurality of optical carrier signals;

a plurality of first optical modulator cells configured to modulate the plurality of optical carrier signals in accordance with components of a first vector to generate a plurality of first modulated optical signals;

multiple sets of second optical modulator cells, each set associated with a corresponding one of multiple second vectors and comprising a plurality of second optical modulator cells configured to modulate the plurality of first modulated optical signals in accordance with components of that second vector to generate a plurality of second modulated optical signals associated with that second vector;

a plurality of waveguide structures each configured to route a corresponding one of the plurality of first modulated optical signals to

corresponding second optical modulator cells of the multiple sets of second optical modulator cells; and

multiple back-end optical combiners each associated with a corresponding one of the multiple second vectors and the associated set of second optical modulator cells and configured to coherently combine the plurality of second modulated optical signals associated with that second vector with uniform power coupling ratios into an optical output signal that represents a scalar product between the first vector and the second vector~~The photonic circuit of claim 1, further comprising,~~ at outputs of the multiple back-end optical combiners, multiple respective optical receivers configured to convert the optical output signals into respective electronic output signals.

~~17~~15. The photonic circuit of claim ~~16~~14, wherein:

the first optical modulator cells are wavelength-division-multiplexed optical modulator cells configured to modulate light at multiple wavelengths in accordance with multiple first vectors; and

the multiple receivers are wavelength-division-multiplexed receivers each configured to generate multiple electronic output signals, the multiple electronic output signals representative of scalar products of the multiple first vectors with the second vector associated with the receiver.

~~18~~16. The photonic circuit of claim ~~17~~15, wherein:

the wavelength-division-multiplexed first optical modulator cells each comprise multiple first modulators corresponding to the multiple first vectors, bracketed between a demultiplexer and a multiplexer; and

the wavelength-division-multiplexed receivers each comprise a demultiplexer followed by multiple receivers to measure electronic output signals representing respective products with the multiple first vectors.

~~19~~17. The photonic circuit of claim ~~16~~14, wherein:

the front-end optical splitter is configured to route the plurality of optical carrier signals from an optical input to the first optical modulator cells along first geometrically delay-matched optical paths;

the plurality of waveguide structures are configured to route the first modulated optical signals from the first optical modulator cells to the second optical modulator cells along second geometrically delay-matched optical paths; and

the multiple back-end optical combiners are configured to route the second modulated optical signals to the receivers along third geometrically delay-matched optical paths.

~~20~~18. The photonic circuit of claim ~~19~~17, wherein the plurality of waveguide structures are configured as symmetric optical waveguide trees with couplers of uniform power coupling ratios at their junctions.

~~21~~19. The photonic circuit of claim ~~20~~18, wherein:

the first optical modulator cells are arranged linearly along a first dimension; and

the second optical modulators cells of all sets of second optical modulators cells are arranged linearly along the first dimension, parallel to the first optical modulator cells, ordered based on their associated first modulated optical signals to form spatial groupings each associated with one of the first modulated optical signals.

~~22~~20. The photonic circuit of claim ~~21~~19, wherein:

the multiple optical receivers are arranged linearly along the first dimension, parallel to the first optical modulator cells and the second optical modulator cells of all sets of second optical modulator cells; and

the second optical modulator cells within each grouping are arranged in a same order as the multiple optical receivers with which they are associated, such that each of the back-end optical combiners combines light from second optical modulator cells at positions within each of the groupings that correspond to a position of the associated optical receiver within the linearly arranged multiple optical receivers.

~~23~~21. The photonic circuit of claim ~~21~~19, wherein:

the multiple optical receivers are arranged linearly along a second dimension that is perpendicular to the first dimension; and

the second optical modulator cells within each of a first half of the groupings along the first dimension are arranged in a same order as the multiple optical receivers with which they are associated and the second optical modulator cells within each of a second half of the groupings along the first dimension are arranged in a reverse order to the multiple optical receivers with which they are associated, such that each of the multiple back-end optical combiners combines light from second optical modulator cells at positions within the groupings that mirror each other between the first half and the second half.

~~24~~22. The photonic circuit of claim ~~21~~19, wherein:

the multiple optical receivers are arranged linearly along a second dimension that is perpendicular to the first dimension; and

the second optical modulator cells are arranged within the groupings alternatingly in a same order as or in a reverse order to the multiple optical receivers with which they are associated, ~~-~~such that each of the multiple back-end optical combiners combines light from second optical modulator cells at positions within the groupings that mirror each other between adjacent groupings along the first dimension.

~~25.~~23 The photonic circuit of claim ~~20~~18, wherein:

the first optical modulator cells are arranged linearly along a first dimension;

the second optical modulator cells within each of the sets are arranged linearly along the first dimension, parallel to the first optical modulator cells; and

the sets of second optical modulator cells are arranged linearly along a second dimension that is perpendicular to the first dimension.

~~26~~24. The photonic circuit of claim ~~16~~14, wherein the optical receivers each comprise a photodetector.

~~27~~25. The photonic circuit of claim ~~16~~14, wherein the optical receivers comprise one or more coherent receivers each including an optical mixer configured to mix the respective optical output signal with a local oscillator signal, a pair of photodetectors to measure intensities of optical outputs of the optical mixer, and an optical amplifier to combine electronic outputs of the pair of photodetectors.

~~28~~26. The photonic circuit of claim 1, wherein each of the back-end optical combiners comprises a cascade of 3dB couplers formed at junctions of an inverse optical waveguide tree, and preceding each of the junctions, a phase shifter in each waveguide of a pair of waveguides combined at the junction.

~~29~~27. The photonic circuit of claim ~~28~~26, wherein, in each pair of waveguides combined at one of the junctions, the phase shifter in one of the waveguides is controlled and the phase shifter in the other one of the waveguides is a dummy phase shifter.

~~30~~28. The photonic circuit of claim 1, wherein the first and second optical modulator cells each comprise an optical amplitude modulator.

~~31~~29. The photonic circuit of claim ~~30~~28, wherein the optical amplitude modulators comprise electronically driven optical devices whose output optical amplitude depends monotonically on a voltage value of a variable drive-signal voltage over a range of voltage values.

~~32~~30. The photonic circuit of claim ~~31~~29, wherein the electronically driven optical devices comprise at least one of electro-absorption modulators or electro-optic ring modulators.

~~33~~31. The photonic circuit of claim ~~31~~29, wherein at least one of the optical amplitude modulators further comprises a Mach-Zehnder interferometer including one of the electronically driven optical devices in one of its interferometer arms, wherein coupling ratios of split and combine couplers of the Mach-Zehnder interferometer are configured such that an optical amplitude at an

output of the Mach-Zehnder interferometer is zero at one end of the range of voltage values of the drive-signal voltage.

~~34~~32. The photonic circuit of claim ~~31~~29, wherein at least one of the optical amplitude modulators further comprises a Mach-Zehnder interferometer including in its two interferometer arms two respective devices of the electronically driven optical devices, wherein the two optical devices are driven differentially.

~~35~~34. The photonic circuit of claim ~~30~~28, wherein at least one of the optical amplitude modulators comprises a Mach-Zehnder interferometer including an electronically driven optical phase shifter in one of its interferometer arms, wherein over a range of voltage values of a variable drive-signal voltage applied to the optical phase shifter, an optical amplitude at an output of the Mach-Zehnder interferometer depends monotonically on a voltage value of the variable drive-signal voltage.

~~36~~34. The photonic circuit of claim ~~30~~28, wherein at least one of the optical amplitude modulators comprises a Mach-Zehnder interferometer including in its two interferometer arms two respective electronically driven optical phase shifters, wherein the two optical phase shifters are driven differentially, and wherein over a range of voltage values of a variable differential drive-signal voltage applied to the optical phase shifters, an optical amplitude at an output of the Mach-Zehnder interferometer depends monotonically on a voltage value of the variable differential drive-signal voltage.

~~37~~35. The photonic circuit of claim ~~30~~28, wherein the optical amplitude modulators are electronically driven by a drive signal voltage created from an analog input, and wherein a transfer function mapping the analog input to the drive signal voltage is configured based on a transfer function from the drive signal voltage to an output optical amplitude of the optical amplitude modulator such that an overall transfer function from the analog input to the output optical amplitude is substantially linear.

38. A method comprising:

receiving coherent light at an optical input;

splitting the coherent light with uniform power coupling ratios into a plurality of optical carrier signals;

routing the optical carrier signals to a plurality of first optical modulator cells;

using the first optical modulator cells to modulate the optical carrier signals in accordance with components of a first vector to generate a plurality of first modulated optical signals;

splitting each of the first modulated optical signals with uniform power coupling ratios between multiple sets of second optical modulator cells associated with multiple respective second vectors;

routing each of the first modulated optical signals to second optical modulator cells, within the multiple sets, that are associated with components of the second vectors corresponding to the component of the first vector associated with the first modulated optical signal;

using the second optical modulator cells of each set to modulate the first modulated optical signals in accordance with corresponding components of the second vector associated with the set to generate second modulated optical signals;

coherently combining the second modulated optical signals associated with each of the second vectors with equal power coupling ratios into an optical output signal associated with the second vector and routing; and

converting the optical output signals associated with the multiple second vectors into respective electronic output signals.

39. The method of claim 38, wherein:

the optical carrier signals are routed to the first optical modulator cells along first geometrically delay-matched optical paths;

the first modulated optical signals are routed to the second optical modulator cells along second geometrically delay-matched optical paths; and

the second modulated optical signals are routed to optical receivers that convert the optical output signals into electronic output signals along third geometrically delay-matched optical paths.

~~40. The method of claim 38, wherein:~~

~~each of the first optical modulator cells is used to demultiplex the optical carrier signal into optical carrier signals at multiple wavelengths, modulate the optical carrier signals at the multiple wavelengths with multiple corresponding first amplitude modulators in accordance with multiple first vectors, and multiplex the modulated optical carrier signals at the multiple wavelengths into the first modulated optical signal; and~~

~~converting the optical output signals associated with the multiple second vectors into respective electronic output signals comprises demultiplexing the optical output signals into optical output signals at the multiple wavelengths, and converting the optical output signals at the multiple wavelengths separately into electronic output signals.~~

~~41. The method of claim 38, further comprising balancing optical losses across optical paths from the optical input to optical receivers that convert the optical output signals into electronic output signals.~~