CLAIMS

What is claimed is:

1. A system comprising a photonic circuit that includes:

an optical splitter configured to split carrier light into a plurality of optical carrier signals;

a plurality of input cells comprising first optical amplitude modulators configured to impart a plurality of computational inputs onto the plurality of optical carrier signals to thereby ~~create~~ output first modulated optical signals;

a plurality of sets of weighting cells, the weighting cells in each set being coupled at their inputs to outputs of the plurality of input cells and comprising a plurality of second optical amplitude modulators configured to impart a plurality of computational weights onto the first modulated optical signals received from the input cells to thereby ~~create~~ output second modulated optical signals associated with the set; and

a plurality of optical combiners each associated with one of the sets of weighting cells and configured to coherently combine the second modulated optical signals associated with the set into an optical output signal.

2. The system of claim 1, wherein the weighting cells of the plurality of sets are arranged in an array comprising a plurality of rows and a plurality of columns, each column of weighting cells corresponding to one of the sets of weighting cells, and each row of weighting cells being associated with and coupled to one of the input cells.

3. The system of claim 2, wherein the photonic circuit further includes a plurality of optical input waveguides, each optical input waveguide being associated with one of the input cells and configured to guide the first modulated optical signal ~~created~~ output in the input cell along the associated row of weighting cells, wherein optical taps placed along each of the optical input waveguides at inputs of the associated weighting cells couple the first modulated optical signal sequentially from the optical input waveguide into the associated weighting cells.

4. The system of claim 3, wherein the optical taps along each of the optical input waveguides are configured to:

couple, to the associated weighting cells, ~~fractions~~ a first portion of an optical power guided in the optical input waveguide that increase in a direction of propagation of the first modulated optical signal, such that the first modulated optical signals coupled into the weighting cells are substantially equal in power along the optical input waveguide; and

pass, to one or more additional weighting cells, a second portion of the optical power.

5. The system of claim 2, wherein each of the optical combiners comprises an optical output waveguide and a plurality of optical couplers placed along the optical output waveguide and configured to sequentially couple the second modulated optical signals from the associated set of weighting cells into the optical output waveguide.

6. The system of claim 1, wherein the optical splitter and the optical combiners are collectively configured to cause the second modulated optical signals associated with each set of weighting cells to be combined into ~~the~~ corresponding optical output signals in equal proportions.

7. The system of claim 1, wherein the optical splitter comprises a cascade of bifurcating splitters that couple the carrier light sequentially to inputs of the plurality of input cells.

8. The system of claim 1, wherein the photonic circuit further includes a plurality of optical delay lines imparting optical delays on the second modulated optical signals to balance optical path lengths between the input cells and an optical output of each of the optical combiners.

9. The system of claim 1, wherein at least one of the first optical amplitude modulators or the second optical amplitude modulators comprise electro-absorption modulators or multi-quantum-confined Stark effect (QCSE) electro-absorption modulators.

10. The system of claim 1, wherein the second optical amplitude modulators comprise optical phase change cells.

11. They system of claim 1, wherein the weighting cells in each set further comprise a plurality of phase shifters associated with the plurality of second amplitude modulators, configurable to impart signs of the computational weights onto the first modulated optical signals.

12. The system of claim 11, wherein the phase shifters comprise at least one of a thermal phase shifter, an electro-optic phase shifter, or a phase-change-material-based phase shifter.

13. The system of claim 1, wherein the photonic circuit further includes a plurality of photodetectors placed at optical outputs of the plurality of optical combiners to measure the optical output signals.

14. The system of claim ~~13~~11, further comprising:

electronic circuitry configured to control drivers associated with the plurality of first optical amplitude modulators, the plurality of second optical amplitude modulators, and the plurality of phase shifters, the electronic circuitry comprising memory storing the computational weights associated with the plurality of weighting cells.

15. The system of claim 14, wherein the optical splitter, the plurality of input cells, the plurality of sets of weighting cells, the plurality of optical combiners, and the plurality of photodetectors implement a first neural network layer, the photonic circuit further comprising an additional optical splitter, an additional plurality of input cells, an additional plurality of sets of weighting cells, an additional plurality of optical combiners, and an additional plurality of photodetectors implementing a second neural network layer, the electronic circuitry being configured to control drivers associated with additional first optical amplitude modulators in the additional input cells of the second layer based on outputs of the plurality of photodetectors of the first layer.

16. The system of claim 14, wherein the electronic circuitry is configured to:

cause a first set of computational weights associated with a first neural network layer to be applied by the plurality of sets of weighting cells;

as the first set of computational weights is applied, causing a first set of computational inputs to be applied by the first optical amplitude modulators and reading out the photodetectors measuring the optical output signals to obtain a first set of computational outputs associated with the first layer;

causing a second set of computational weights associated with a second neural network layer to be applied by the weighting cells; and

as the second set of computational weights is applied, causing a second set of computational inputs based on the first set of computational outputs to be applied by the first optical amplitude modulators and reading out the photodetectors measuring the optical output signals to obtain a second set of computational outputs associated with the second layer.

17. The system of claim 1, wherein:

each of the input cells is associated with a respective one of the computational inputs and configured to impart that computational input, with one of the first optical amplitude modulators, on one of the optical carrier signals to ~~create~~ output one of the first modulated optical signals; ~~and~~

each of the optical combiners and its associated optical output signal are associated with a respective one of a plurality of computational outputs; and

each of the weighting cells is associated with a respective pair of one of the computational inputs and one of the computational outputs, and configured to impart, using one of the second amplitude modulators, one of the computational weights on the first modulated optical signals associated with that computational input to ~~create~~ output one of the second modulated optical signals.

18. The system of claim 1, wherein the carrier light is multiplexed light, the optical carrier signals are multiplexed optical carrier signals, and the optical output signals are multiplexed optical output signals.

19. The system of claim 18, wherein the input cells each comprise a set of multiple first optical amplitude modulators associated with multiple wavelengths of the multiplexed optical carrier signals, preceded by a demultiplexer and followed by a multiplexer, the multiple first

optical amplitude modulators in each input cell configured to ~~create~~ output multiple respective first modulated optical signals by imparting multiple computational inputs onto the multiple wavelengths of the multiplexed optical carrier signals.

20. The system of claim 18, wherein the weighting cells each comprise a set of multiple second optical amplitude modulators and/or phase shifters associated with multiple wavelengths of the multiplexed optical carrier signals, preceded by a demultiplexer and followed by a multiplexer, the multiple second optical amplitude modulators and/or phase shifters configured to ~~create~~ output multiple respective second modulated optical signals by imparting multiple computational weights onto one or more first modulated optical signals.

21. The system of claim 18, further comprising electro-optic switches preceding and following each of the input cells and each of the weighting cells, the electro-optic switches configurable to direct ~~the~~ multiplexed optical input signals along first or second input optical paths through the input cells and along first or second weighting optical paths through the weighting cells, wherein:

each of the input cells comprises a set of first optical amplitude modulators associated with multiple wavelengths of the multiplexed optical carrier signals and preceded by a demultiplexer and followed by a multiplexer along the first input optical path, and a separate first optical amplitude modulator along the second input optical path; and

each of the weighting cells comprises a set of second optical amplitude modulators and/or phase shifters associated with multiple wavelengths of the multiplexed optical carrier signals and preceded by a demultiplexer and followed by a multiplexer along the first weighting optical path, and a separate second optical amplitude modulator and/or phase shifter along the second weighting optical path.

22. The system of claim 21, wherein the electro-optic switches are programmable for a plurality of configurations implementing a plurality of associated artificial neural network types, the plurality of configurations comprising:

a convolutional neural network configuration in which the multiplexed optical carrier signals are directed along the first input optical paths and the second weighting optical paths;

a fully connected neural network configuration in which the multiplexed optical carrier signals are directed along the second input optical paths and the first weighting optical paths; and

a neural network configuration in which the multiplexed optical input signals are directed along the first input optical paths and the first weighting optical paths.

23. A photonic circuit comprising:

an optical splitter configured to split multiplexed light into a plurality of multiplexed optical carrier signals associated with a plurality of inputs;

a plurality of interferometric optical paths configured to receive the plurality of multiplexed optical carrier signals and generate multiplexed weighted optical input signals; and

an optical combiner configured to combine the multiplexed weighted optical input signals into a multiplexed optical output signal,

wherein each interferometric optical path of the plurality of interferometric optical paths comprises:

a first electro-optical switch, a second electro-optical switch, and a third electro-optical switch, the first and second electro-optical switches configurable to switch the plurality of multiplexed optical carrier signals between first and second input optical paths and the second and third electro-optical switches configurable to switch multiplexed optical input signals between first and second weighting optical paths;

between the first and second electro-optical switches, an input cell comprising a set of first optical amplitude modulators associated with multiple wavelengths of the plurality of multiplexed optical carrier signals and preceded by a demultiplexer and followed by a multiplexer along the first input optical path, and a separate first optical amplitude modulator along the second input optical path, the input cell configured to generate the multiplexed optical input signals; and

between the second and third electro-optical switches, a weighting cell comprising a set of second optical amplitude modulators and phase shifters associated with multiple wavelengths of the plurality of multiplexed optical carrier signals and preceded by a demultiplexer and followed by a multiplexer along the first weighting optical path, and a separate second optical amplitude modulator and phase shifter along

the second weighting optical path, the weighting cell configured to generate the multiplexed weighted optical input signals.

24. The photonic circuit of claim 23, further comprising a demultiplexer at an output of the optical combiner, the demultiplexer configured to separate the multiplexed optical output signal into optical output signals of multiple wavelengths.

25. The photonic circuit of claim 24, further comprising a plurality of photodetectors to measure the optical output signals at the multiple wavelengths.

26. A photonic computing method comprising:

splitting light into a plurality of optical carrier signals associated with a plurality of computational inputs;

modulating amplitudes of the plurality of optical carrier signals to impart the computational inputs onto the optical carrier signals, thereby ~~creating~~ outputting a plurality of first modulated optical signals;

splitting each of the optical input signals between a plurality of optical paths associated with a plurality of computational outputs;

modulating amplitudes and/or phases of the first modulated optical signals in each of the plurality of optical paths to impart computational weights, each associated with one of the plurality of computational inputs and one of the plurality of computational outputs, onto the first modulated optical signals, thereby generating second modulated optical signals; and

coherently combining, for each of the computational outputs, the second modulated optical signals in optical paths associated with the computational output into an optical output signal encoding the computational output.

27. The method of claim 26, wherein each of the optical carrier signals is associated with one of the plurality of computational inputs, and each of the optical output signals is associated with one of the plurality of computational outputs.

28. The method of claim 26, wherein the light is multiplexed light comprising multiple wavelengths, the optical carrier signals are multiplexed optical carrier signals each associated with multiple computational inputs imparted on the optical carrier signal at the multiple wavelengths to ~~create~~ output multiple first modulated optical signals, and the optical output signals are multiplexed optical output signals associated with multiple computational outputs encoded in the optical output signal at the multiple wavelengths.

~~29. A computing system comprising:~~

~~a photonic integrated circuit (PIC) implementing one or more computational layers, the PIC comprising:~~

~~one or more coherent photonic crossbars each configured to modulate a plurality of optical input signals to impart computational weights associated with a plurality of sets of weights onto the optical input signals to create weighted optical input signals, and to coherently combine the weighted optical input signals to generate optical output signals encoding computational outputs associated with the plurality of sets of weights,~~

~~at least one of the one or more coherent photonic crossbars comprising a plurality of electronically controlled modulators to impart computational inputs onto coherent optical carrier signals to generate the plurality of optical input signals, and~~

~~at least one of the one or more coherent photonic crossbars comprising a plurality of photodetectors to generate analog electronic output signals based on the optical output signals; and~~

~~a mixed-signal electronic integrated circuit (EIC) comprising:~~

~~driver circuitry to control the modulators in the PIC in accordance with the computational inputs, and~~

~~processing circuitry to process the analog electronic output signals, the processing being performed at least partially digitally.~~

~~30. The computing system of claim 29, wherein the one or more coherent photonic crossbars implement multiple computational layers.~~

~~31. The computing system of claim 30, wherein the analog electronic output signals associated with one of the multiple computational layers are processed to generate control signals for the driver circuitry associated with the computational inputs of another one of the computational layers.~~

~~32. The computing system of claim 31, wherein at least one of the one or more coherent photonic crossbars comprises a plurality of additional electronically controlled modulators to impart the computational weights onto the optical input signals, and wherein the EIC further comprises additional driver circuitry to control the additional modulators.~~

~~33. The computing system of claim 32, wherein the one of the computational layers and the other one of the computational layers are implemented by a single one of the one or more coherent photonic crossbars, and wherein the additional driver circuitry controls the additional modulators in accordance with one set of computational weights to implement the one of the computational layers and in accordance with another set of computational weights to implement the other one of the computational layers.~~

~~34. The computing system of claim 32, wherein the EIC further comprises memory storing the computational weights and digital-to-analog converters to generate, from the computational weights, control signals for the additional driver circuitry.~~

~~35. The computing system of claim 32, wherein the additional electronically controlled modulators comprise pairs of an amplitude modulator and a phase shifter to impart signed computational weights onto electric fields of the optical input signals.~~

~~36. The computing system of claim 31, wherein the one of the computational layers and the other one of the computational layers are implemented by two coherent photonic crossbars.~~

~~37. The computing system of claim 30, wherein the multiple computational layers are implemented by multiple coherent photonic crossbars, and wherein the optical output signals of at least one of the coherent photonic crossbars are provided to another one of the coherent photonic crossbars as the optical input signals.~~

~~38. The computing system of claim 29, further comprising at least one of optical amplifiers in the PIC to amplify the optical output signals or electronic amplifiers in the processing circuitry to amplify the analog electronic output signal.~~

~~39. The computing system of claim 29, wherein the one or more computational layers represent one or more neural network layers, the plurality of sets of weights represent a plurality of neurons, and the computational outputs are linear neuron outputs.~~

~~40. The computing system of claim 39, wherein the processing circuitry applies a non-linear electronic activation function to the analog electronic signals either in an analog domain or in a digital domain following analog-to-digital conversion.~~

~~41. The computing system of claim 39, wherein the PIC further comprises non-linear activation units associated with the neurons of at least one of the one or more coherent photonic crossbars, the non-linear optical activation units configured to apply an optical non-linearity to the optical output signals encoding the linear neurons outputs to thereby generate optical output signals encoding non-linear neuron outputs.~~

~~42. The computing system of claim 39, wherein the digital processing comprises a neural-network-layer operation.~~

~~43. The computing system of claim 42, wherein the neural-network-layer operation implements one of a pooling layer or a fully-connected layer.~~

~~44. The computing system of claim 39, wherein the digital processing comprises an image pre-processing operation for image input to the one or more neural network layers or a post-processing operation of output generated by the one or more neural network layers.~~

~~45. The computing system of claim 44, wherein the digital processing comprises adjusting stored neural network weights to enable structural sparsity.~~

~~46. The computing system of claim 29, wherein at least one of the PIC or the EIC is configured to perform mixed-precision operations.~~

~~47. The computing system of claim 29, wherein the EIC further comprises a graphic processing unit (GPU) core to perform at least part of the digital processing.~~

~~48. The computing system of claim 29, wherein the EIC further comprises on-chip memory.~~

~~49. The computing system of claim 29, further comprising an electronic interface between the PIC and the EIC, the electronic interface having a power consumption of less than 3 pJ per bit of data converted from an optical domain to a digital electronic domain or from a digital electronic domain to an optical domain.~~

~~50. The computing system of claim 29, the PIC further comprising an optical splitter that receives carrier light from a light engine and splits it into the coherent optical carrier signals.~~

~~51. The computing system of claim 50, wherein the light engine comprises a plurality of lasers generating light at multiple wavelengths and a multiplexer to combine the light at the multiple wavelengths into multiplexed carrier light.~~

~~52. The computing system of claim 29, the PIC further comprising an optical interface that receives carrier light from a source external to the PIC, the optical interface comprising at least one of an edge coupler, inverted taper coupler, or grating coupler.~~

~~53. The computing system of claim 52, wherein the optical interface comprises at least one of an edge coupler, an inverted taper coupler, or a grating coupler.~~

~~54. The computing system of claim 29, wherein the digital processing comprises operations performed at higher bit precision than operations performed in the PIC.~~