

SYSTEMS AND METHODS FOR NON-RECIPROCAL MAGNETO-OPTICS**CROSS-REFERENCE TO RELATED APPLICATIONS**

[0001] The present application claims the benefit of and priority to U.S. Provisional Application No. 63/608,796, filed December 11, 2023, which is incorporated by reference herein in its entirety.

TECHNICAL FIELD

[0002] This disclosure relates to non-reciprocal magneto-optics, more specifically for managing data and/or sensing an external magnetic field.

BACKGROUND

[0003] There is a growing divide between demand for computing resources and the performance of digital hardware.

SUMMARY

[0004] The present disclosure relates to devices, systems, and methods involving non-reciprocal magneto-optics. Optical weights can be encoded for in-memory photonic computing using magneto-optic memory cells, which can be made of heterogeneously integrated cerium yttrium iron garnet on silicon microring resonators.

[0005] One aspect of the present disclosure provides a device. The device can include a waveguide. The waveguide can include a first segment and a second segment. The device can include a plurality of rings disposed between the first segment and the second segment. The plurality of rings can be made of a magneto-optic material. The magneto-optic material can exhibit a non-reciprocal phase shift. The device can include an analyzer. The analyzer can receive first light from the first segment and second light from the second segment.

[0006] In one embodiment, the device can include one or more magnets disposed proximate to each of the plurality of rings. The one or more magnets can be made of a ferromagnetic material. The device can include an electromagnet. The electromagnet can generate a magnetic field to modify a plurality of magnetic moments of the one or more magnets.

[0007] In one embodiment, the one or more magnets can encode a plurality of optical weights. In one embodiment, the one or more magnets are disposed between the electromagnet and the plurality of rings. The plurality of rings can be disposed between the one or more magnets and the waveguide. The waveguide can be disposed between the one or more magnets and the plurality of rings. In one embodiment, the one or more magnets is made of CoFeB.

[0008] In one embodiment, the waveguide can guide the first light through the first segment of the waveguide proximate to the plurality of rings, which are each configured to be excited in a clockwise propagating mode. The waveguide can guide the second light through the second segment of the waveguide proximate to the plurality of rings, which are each configured to be excited in a counterclockwise propagating mode. In one embodiment, the analyzer can detect a resonance split between the clockwise propagating mode and the counterclockwise propagating mode for each of the plurality of rings.

[0009] In one embodiment, the magneto-optic material can exhibit the non-reciprocal phase shift due to at least one of light, a current, spin-orbit torque, or a magnetic field. The non-reciprocal phase shift of the magneto-optic material can include a property of the magneto-optic material such that the property has a first value when light passes through the magneto-optic material in a first direction and the property has a second value different from the first value when light passes through the magneto-optic material in a second direction different from the first direction. The non-reciprocal phase shift of the magneto-optic material can include opposite resonance shifts for a clockwise propagating mode and a counterclockwise propagating mode.

[0010] In one embodiment, the magneto-optic material is made of cerium yttrium iron garnet. In one embodiment, the analyzer determines one or more states of an external magnetic field. A portion of each of the plurality of rings can be shielded from the external magnetic field. In one embodiment, the waveguide can include a y-splitter.

[0011] Another aspect of the present disclosure provides a method. The method can include managing data using a device. The device can have a plurality of rings. The plurality of rings can be coupled with a layer. The layer can be made of a magneto-optic material. The magneto-optic material can exhibit a non-reciprocal phase shift. The method can include generating a magnetic field. The method can include modifying, by the magnetic field, a plurality of magnetic moments of one or more magnets disposed proximate to each of the

plurality of rings. The one or more magnets can be made of a ferromagnetic material to store the data corresponding to one or more strengths and one or more directions of the magnetic field. The method can include passing first light through a first segment of a waveguide. The waveguide can guide the first light through the first segment of the waveguide proximate to the plurality of rings, which are each configured to be excited in a clockwise propagating mode. The method can include passing second light through a second segment of the waveguide. The waveguide can guide the second light through the second segment of the waveguide proximate to the plurality of rings, which are each configured to be excited in a counterclockwise propagating mode. The method can include receiving, by an analyzer, the first light from the first segment and the second light from the second segment for each of the plurality of rings to retrieve the data from the one or more magnets.

[0012] In one embodiment, the method includes adjusting the plurality of magnetic moments of the one or more magnets subsequent to receiving, by the analyzer, the first light and the second light. In one embodiment, the method includes outputting a plurality of spectra corresponding to a plurality of optical weights. In one embodiment, the data corresponds to one or more optical transmission levels.

[0013] Another aspect of the present disclosure provides a method. The method can include sensing an external magnetic field using a device. The device can have a plurality of rings. The plurality of rings can be coupled with a layer. The layer can be made of a magneto-optic material. The magneto-optic material can exhibit a non-reciprocal phase shift. The method can include passing first light through a first segment of a waveguide. The waveguide can guide the first light through the first segment of the waveguide proximate to the plurality of rings, which are each configured to be excited in a clockwise propagating mode. The method can include passing second light through a second segment of the waveguide. The waveguide can guide the second light through the second segment of the waveguide proximate to the plurality of rings, which are each configured to be excited in a counterclockwise propagating mode. The method can include receiving, by an analyzer, the first light from the first segment and the second light from the second segment for each of the plurality of rings.

[0014] In one embodiment, the method includes shielding a portion of each of the plurality of rings from the external magnetic field. In one embodiment, the method includes outputting a plurality of spectra corresponding to a plurality of optical weights.

[0015] Both the foregoing summary and the following description of the drawings and detailed description are exemplary and explanatory. They are intended to provide further details but are not to be construed as limiting. Other objects, advantages, and novel features will be readily apparent to those skilled in the art from the following detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] FIGS. 1A-1H illustrate non-reciprocal photonic in-memory computing, in accordance with one or more embodiments shown and described herein.

[0017] FIGS. 2A, 2B, 2C, 2G, and 2H illustrate non-reciprocal photonic computing, in accordance with one or more embodiments shown and described herein.

[0018] FIGS. 2D, 2E, 2F, 2I, and 2J illustrate reciprocal photonic computing.

[0019] FIGS. 3A-3E illustrate experimental characterizations of non-reciprocal optical memory, in accordance with one or more embodiments shown and described herein.

[0020] FIGS. 4A-4G illustrate dynamic responses of non-reciprocal optical memory, in accordance with one or more embodiments shown and described herein.

[0021] FIG. 5A illustrates a cross-section of a device, in accordance with one or more embodiments shown and described herein.

[0022] FIG. 5B illustrates a profile of the transverse magnetic optical mode, in accordance with one or more embodiments shown and described herein.

[0023] FIG. 6 illustrates the effective index of the transverse mode versus wavelength, in accordance with one or more embodiments shown and described herein.

[0024] FIGS. 7A-7D illustrate temperature variation, in-plane magnetic field, refractive index variation, and the magneto-optic effect, in accordance with one or more embodiments shown and described herein.

[0025] FIG. 8A and 8B illustrate amplitude and phase of the transfer function for the clockwise and counterclockwise mode, in accordance with one or more embodiments shown and described herein.

[0026] FIG. 9 illustrates the measurement set-up for high-speed characterization, in accordance with one or more embodiments shown and described herein.

[0027] FIG. 10 illustrates a flow chart of an example method of managing data, in accordance with one or more embodiments shown and described herein.

[0028] FIG. 11 illustrates a flow chart of an example method of sensing an external magnetic field, in accordance with one or more embodiments shown and described herein.

[0029] Like reference numbers and designations in the various drawings indicate like elements.

DETAILED DESCRIPTION

I. Overview

[0030] Processing information in the optical domain can offer advantages in both speed and energy efficiency over digital hardware for a variety of emerging applications in artificial intelligence and machine learning. One approach to photonic processing is to multiply a rapidly changing optical input vector with a matrix of fixed optical weights. However, encoding these weights on-chip using an array of photonic memory cells can be limited by a wide range of materials-level and device-level issues, such as the programming speed, extinction ratio, endurance, and more.

[0031] The present disclosure is directed to systems and methods to encode optical weights for in-memory photonic computing using magneto-optic memory cells. The cells can be made of heterogeneously integrated cerium yttrium iron garnet (Ce:YIG) on silicon microring resonators. Leveraging the non-reciprocal phase shift in such magneto-optic materials can provide a fast (e.g., 1 ns), efficient (e.g., 143 fJ per bit), and robust (e.g., 2.4 billion programming cycles) platform for on-chip optical processing. An integrated photonic computing architecture can leverage the non-reciprocal phase shift in magneto-optic materials. A y-splitter can excite both the clockwise (CW) and counterclockwise (CCW) propagating modes within a microring resonator cladded with Ce:YIG. The interaction of the optical mode with the Ce:YIG can cause a

non-reciprocal phase shift for two counter-propagating modes (e.g., clockwise propagating mode and counterclockwise propagating mode). This can be visible as a resonance shift with opposite signs. The direction of the non-reciprocal phase shift can depend on the sign of an applied external magnetic field, which can allow for both positive and negative weights to be encoded through balanced photodetection measured at the output of the CW and CCW through-ports.

[0032] Post-CMOS (complementary metal-oxide-semiconductor) architectures which can achieve ultra-high computational throughput at ultra-low energies are of interest to address the divide between demand for computing resources and the performance of digital hardware. In the field of deep learning, for example, the computation required to train state-of-the-art DNNs grew by over 300,000 times between 2015 and 2020, while computing efficiency grew by about 10 times. Additionally, for emerging applications, such as high-speed qubit classification, plasma control in fusion reactors, real-time RF signal processing, and autonomous navigation, processing data with ultra-low latencies can be challenging using digital approaches, which can rely on sequential arithmetic operations.

[0033] Processing information in the optical domain can address the energy-bandwidth trade-off of fully electronic hardware. For optical interconnects, energy consumption can be independent of optical modulation speeds, while weak photon-photon interactions can allow high bandwidth density through frequency multiplexing. Additionally, by breaking free from the confines of binary logic and encoding, linear operations (e.g., convolutions, matrix multiplications, Fourier transforms, random projections, etc.) can be reduced to a single optical transmission measurement with extremely low energy consumption—even less than one photon per multiply-accumulate operation. These combined advantages of analog computing in the optical domain can allow for the dramatic scaling for continued innovations in artificial intelligence (AI) and machine learning—both in terms of compute density (e.g., operations per chip area) and energy efficiency (e.g., operations per watt).

[0034] Many distinct photonic architectures can attempt to address the major bottleneck facing the field of AI and computing: matrix-vector multiplication (MVM). The vast majority of these approaches can be classified as “weight-stationary” photonic processors where a matrix of programmable optical weights—typically encoded in a 2D array of non-volatile memory elements or optical modulators—is used to perform a linear transformation on a vector of optical

inputs. This design approach can perform computation in the memory array itself, not unlike analog computing in the electrical domain using crossbar arrays of resistive random-access memory (RRAM), which can significantly reduce data movement and latency, while improving energy efficiency.

[0035] However, a limitation of these weight-stationary approaches is the time and energy which can be required to update the fixed weights of the matrix to implement useful computing algorithms. Compared to demonstrations of in-memory computing using electronic crossbar arrays, optical weight banks can have much lower storage density (e.g., ~ 0.01 bits/ μm^2) and can only store a small fraction of the parameters on-chip (e.g., a 16×16 phase-change memory array or 64×64 Mach-Zehnder interferometer array). Thus, to accommodate the large number of parameters which can be required by real-world applications, the photonic weight bank may have to be reprogrammed many times for each matrix operation that exceeds the dimensions of the weight bank. This can require photonic memory cells which can be deterministically programmed quickly, efficiently, and with high endurance. Without these properties, the throughput and energy efficiency of the entire system can be reduced.

II. Exemplary Structures

[0036] The systems and methods of the present disclosure can include a resonance-based photonic architecture, which leverages the non-reciprocal phase shift in magneto-optical materials to implement in-memory photonic computing. The systems and methods of the present disclosure can include integrated non-reciprocal magneto-optics with ultra-high endurance for photonic in-memory computing. In this architecture (as shown in FIG. 1A), a y-splitter can excite both the clockwise (CW) and counterclockwise (CCW) propagating modes of a microring resonator (MRR) with a magneto-optic cladding layer made of cerium-substituted yttrium iron garnet (Ce:YIG). The Ce:YIG can include heterogeneously integrated Ce:YIG. FIG. 1A illustrates a single row of the architecture which leverages non-reciprocal magneto-optic MMR memory elements to implement a dot-product. The interaction of the optical mode with Ce:YIG can cause a non-reciprocal phase shift for the two counterpropagating modes which is visible as a split resonance shift with opposite signs. The direction of the non-reciprocal phase shift can be dependent on the sign of an applied external magnetic field which allows both positive and negative weights to be encoded (as shown in FIGS. 1F and 1G). A circulator can be used to

prevent feedback to the optical source for the case of an add-drop MRR or, in the case of an all-pass MRR, a pair of circulators can be used (as shown in FIGS. 1B and 1C).

[0037] This approach can have a number of benefits. First, by using the non-reciprocal effect in magneto-optic materials, programming speeds on the order of 1 GHz, non-volatility, and multi-level encoding can be achieved. Second, the cycling endurance of magnetic-based memory can be orders of magnitude greater than other technologies, which can be an outstanding challenge for many non-volatile optical memories. Third, unlike the case of add-drop MRR weights based on reciprocal optical effects (e.g., thermo-optic or plasma-dispersion effects), the differential signal can be measured from the through port transmission for both the CW and CCW modes, improving the symmetry and extinction ratio for both positive and negative weighting.

[0038] FIG. 1A illustrates a device 100 for non-reciprocal photonic in-memory computing. The device 100 can manage data by storing data and reading data stored in memory. The device 100 can be used to write memory electrically and read memory optically. The device 100 can be used to encode information. The device 100 can include computing combined with memory storage. The device 100 can include an integrated photonic computing architecture. The device 100 can operate as a sensor to detect an external magnetic field. The device 100 can operate at various temperatures, including, for example, cryogenic temperatures (e.g., less than 120 K).

[0039] The device 100 can include one or more waveguides 105. The waveguide 105 can include an optical fiber. The waveguide 105 can support one or more optical signals. For example, the waveguide 105 can transmit light having one or more frequencies. The waveguide 105 can transmit light having one or more wavelengths. The waveguide 105 can include a bus waveguide. The waveguide can include a silicon waveguide. The waveguide can receive input light. The input light can be output from a laser.

[0040] The waveguide 105 can include one or more segments 110. For example, the waveguide 105 can include a first segment. The waveguide 105 can include a second segment. The first segment and the second segment can be separated by a distance. The first segment and the second segment can be substantially parallel. The waveguide 105 can include a y-splitter. For example, the waveguide 105 can split into the first segment and the second segment. The input

light can be separated into first light and second light. The first light can pass through the first segment. The waveguide 105 can guide the first light through the first segment of the waveguide 105. The second light can pass through the second segment. The waveguide 105 can guide the second light through the first segment of the waveguide 105.

[0041] The device 100 can include a plurality of rings 115. The ring 115 can include a microring resonator (e.g., microring, ring resonator). The ring 115 can have circular shape. The ring 115 can include a closed-loop surface waveguide. The ring 115 can support a resonant condition. The ring 115 can have a closed-loop shape. The closed-loop shape can include a circle, ellipse, oval, squares, rectangles, racetracks, stadiums, etc. The plurality of rings 115 can be disposed between the first segment and the second segment. The plurality of rings 115 can be disposed above, below, or to the side of the waveguide 105. The plurality of rings 115 can be optically coupled to the waveguide 105. For example, the plurality of rings 115 can be optically coupled to the first segment of the waveguide 105. The plurality of rings 115 can be optically coupled to the second segment of the waveguide 105. The plurality of rings 115 can be excited in a mode (e.g., clockwise propagating mode, counterclockwise propagating mode). The plurality of rings 115 can resonate. For example, the plurality of rings 115 can resonate in the opposite direction as the input light.

[0042] The device 100 can include one or more layers 120. The plurality of rings 115 can be coupled with the layer 120. For example, the layer 120 can be disposed on the plurality of rings 115. The layer 120 can be made of a magneto-optic material. The plurality of rings 115 can be made of a magneto-optic material. The magneto-optic material can be made of cerium yttrium iron garnet (Ce:YIG). The plurality of rings 115 can be cladded with the magneto-optic material. The magneto-optic material can exhibit non-reciprocity. For example, the magneto-optic material can exhibit non-reciprocity with respect to polarization, loss, and/or phase. Polarization can include the geometrical orientation of light oscillations. Loss can include propagation loss in a medium. Phase can include the speed of light in the medium. The magneto-optic material can exhibit a non-reciprocal property. The magneto-optic material exhibiting non-reciprocity can have an anti-symmetric function with respect to encoded weight values. This can be in contrast to optical materials and/or magneto-optic materials exhibiting reciprocity, which can have symmetric functions with respect to encoded weight values. One or more properties of the magneto-optic material can be modified the light or a magnetic field. The plurality of rings 115

can be made of silicon. The plurality of rings 115 can include silicon and one or more cladding layers. The plurality of rings 115 can be disposed adjacent to the one or more cladding layers. The cladding layer (e.g., layer 120) can be made of a magneto-optic materials. For example, the cladding layer can be made of Ce:YIG. In some embodiment magneto-optic garnet can be monolithically integrated on silicon and silicon nitride substrates. The plurality of rings 115 can be coupled to the cladding layer. For example, the plurality of rings 115 can be coupled to the cladding layer of magneto-optic material via the evanescent field of the plurality of rings 115 and/or waveguide 105. The plurality of rings 115 can be covered with a magneto-optic material and interact via the evanescent field of the plurality of rings 115. The plurality of rings 115 can be coupled to a magneto-optic material via evanescent coupling. The plurality of rings 115 can include silicon coupled with a magneto-optic material. The plurality of rings 115 can include silicon coupled with the layer 120.

[0043] The magneto-optic material can exhibit a non-reciprocal phase shift. The magneto-optic material can exhibit the non-reciprocal phase shift due to at least one of light, a current, spin-orbit torque, or a magnetic field. The magnetic field can include an external magnetic field. The non-reciprocal phase shift of the magneto-optic material can include a property of the magneto-optic material such that the property has a first value when light passes through the magneto-optic material in a first direction and the property has a second value different from the first value when light passes through the magneto-optic material in a second direction different from the first direction. The non-reciprocal phase shift of the magneto-optic material can include opposite resonance shifts for a clockwise propagating mode and a counterclockwise propagating mode. Light can induce a non-reciprocal phase shift for the two counter-propagating modes. Light can induce a non-reciprocal phase shift in each of the plurality of rings 115.

[0044] The waveguide 105 can guide the first light through the first segment of the waveguide 105 proximate to the plurality of rings 115. The plurality of rings 115 can each be configured to be excited in the clockwise propagating mode. The first light can excite the clockwise propagating mode in the plurality of rings 115. Portions of the first light can excite individual rings of the plurality of rings. For example, a first portion of the first light can excite a first ring of the plurality of rings 115. The first portion of the first light can have a first wavelength. A second portion of the first light can excite a second ring of the plurality of rings

115. The second portion of the first light can have a second wavelength. A third portion of the first light can excite a third ring of the plurality of rings 115. The third portion of the first light can have a third wavelength. A fourth portion of the first light can excite a fourth ring of the plurality of rings 115. The fourth portion of the first light can have a fourth wavelength.

[0045] The waveguide 105 can guide the second light through the second segment of the waveguide 105 proximate to the plurality of rings 115. The plurality of rings 115 can each be configured to be excited in the counterclockwise propagating mode. The second light can excite the counterclockwise propagating mode in the plurality of rings 115. Portions of the second light can excite individual rings of the plurality of rings. For example, a first portion of the second light can excite the first ring of the plurality of rings 115. The first portion of the second light can have the first wavelength. A second portion of the second light can excite the second ring of the plurality of rings 115. The second portion of the second light can have the second wavelength. A third portion of the second light can excite the third ring of the plurality of rings 115. The third portion of the second light can have the third wavelength. A fourth portion of the second light can excite the fourth ring of the plurality of rings 115. The fourth portion of the second light can have the fourth wavelength. The first light and the second light can induce a non-reciprocal phase shift for the two counter-propagating modes.

[0046] The device 100 can include one or more analyzers 125. The analyzer 125 can include a CW through-port and a CCW through-port. The analyzer 125 can receive first light from the first segment. For example, the analyzer 125 can receive the portions of the first light after the first light has been modified by the plurality of rings 115. The analyzer 125 can receive the first portion of the first light, the second portion of the first light, the third portion of the first light, and the fourth portion of the first light after each of the portions of light have been modified by the plurality of rings 115. The analyzer 125 can be, for example, implemented as a light collection device. The analyzer 125 can include one or more ports. The analyzer 125 can include a photodetector and/or photosensor. The analyzer 125 can include a sensor (e.g., light sensor). The analyzer 125 can include a spectrometer. The analyzer 125 can include a data acquisition unit. The analyzer 125 can include a digital communication analyzer.

[0047] The analyzer 125 can receive second light from the second segment. For example, the analyzer 125 can receive the portions of the second light after the second light has been

modified by the plurality of rings 115. The analyzer 125 can receive the first portion of the second light, the second portion of the second light, the third portion of the second light, and the fourth portion of the second light after each of the portions of light have been modified by the plurality of rings 115. The first portion of the second light can be the same as or different from the first portion of the first light. The second portion of the second light can be the same as or different from the second portion of the first light. The third portion of the second light can be the same as or different from the third portion of the first light. The fourth portion of the second light can be the same as or different from the fourth portion of the first light.

[0048] The analyzer 125 can detect a resonance split between the clockwise propagating mode and the counterclockwise propagating mode for each of the plurality of rings 115. The resonance split can correspond to $-2\Delta\lambda_{MO}$ or $+2\Delta\lambda_{MO}$. The resonance split can be used to encode positive and/or negative weights. The term $-2\Delta\lambda_{MO}$ can correspond to a negative weight. The term $+2\Delta\lambda_{MO}$ can correspond to a positive weight.

[0049] The analyzer 125 can determine one or more states of the external magnetic field. For example, device 100 can be used as a sensor to determine the one or more states of the external magnetic field. The state of the external magnetic field can include the magnitude and direction of the external magnetic field. The external magnetic field can originate from, for example, one or more transformers. A portion of each of the plurality of rings 115 can be shielded from the external magnetic field. For example, the portion of each of the plurality of rings 115 can be covered or protected from the external magnetic field. The plurality of rings 115 can be partially covered.

[0050] The device 100 can include one or more electromagnets 130. The electromagnet 130 can generate a magnetic field. For example, the electromagnet 130 can generate the magnetic field. The electromagnet 130 can include a magnet in which the magnetic field is produced by an electric current. The electromagnet 130 can include an electrically conductive material, such as gold and/or chromium. The electromagnet 130 can have substantially the same shape as the ring 115. The electromagnet 130 can include a loop conductor and two terminals.

[0051] The device 100 can include one or more magnets 135. The one or more magnets 135 can be disposed proximate to each of the plurality of rings 115. The one or more magnets 135 can form a shape, such as a circle or ring. For example, a plurality of magnets 135 can be

disposed along a circle between the first segment of the waveguide 105 and the second segment of the waveguide 105. The one or more magnets 135 can be disposed above, below, or to the side of the plurality of rings 115. The one or more magnets 135 and the plurality of rings 115 can be separated by a distance. Each set of the one or more magnets 135 disposed proximate to each of the plurality of rings 115 can form a memory unit. Each memory unit can store a value (e.g., positive value, negative value, zero). The analyzer 125 can read the weights (e.g., memory) encoded by the one or more magnets 135. Light can be used to read the weights encoded by the one or more magnets 135. The one or more magnets 135 can impose a magnetic field on the plurality of rings 115. The one or more magnets 135 modify a property of the magneto-optic material. The electromagnet 130 can write the weights to the one or more magnets 135. Other methods of writing the weights can include passing current, shining light, applying an external magnetic field, using spin-orbit torque. Writing the weights can include switching the weights.

[0052] The one or more magnets 135 can include a ferromagnetic material. For example, the one or more magnets 135 can be made of a ferromagnetic material. The one or more magnets 135 be made of a ferromagnetic thin film. The one or more magnets 135 can include a switchable layer (e.g., switchable ferromagnetic layer). The one or more magnets 135 can be made of CoFeB. The one or more magnets 135 can be made of a ferromagnetic thin-film. The one or more magnets 135 can be made of iron, nickel, or cobalt. The one or more magnets 135 can include one or more permanent magnets. The plurality of magnetic moments of the one or more magnets 135 can be modified. For example, the magnetic field from the electromagnet can modify the plurality of magnetic moments of the one or more magnets 135. An external magnetic field can modify the plurality of magnetic moments of the one or more magnets 135. Modifying the plurality of magnetic moments of the one or more magnets 135 can include changing one or more of the magnetic strength or orientation of the plurality of magnetic moments of the one or more magnets 135.

[0053] The one or more magnets 135 can encode a plurality of optical weights. The plurality of optical weights can correspond to one or more strengths and/or one or more directions of the magnetic field. The one or more magnets 135 can store data corresponding to one or more strengths and/or one or more directions of the magnetic field. The data can correspond to the plurality of magnetic moments of the one or more magnets 135. The data can include a set of values. Each of the values can have a magnitude and a sign (e.g., positive or

negative). The strength of the magnetic field can correspond to the magnitude of the value. The direction of the magnetic field can correspond to the sign of the value. The one or more magnets 135 can include media to store information (e.g., optical weights).

[0054] The one or more magnets 135 can be disposed between the electromagnet 130 and the plurality of rings 115. The plurality of rings 115 can be disposed between the one or more magnets 135 and the waveguide 105. The waveguide 105 can be disposed between the one or more magnets 135 and the plurality of rings 115. The waveguide 105 can be above, below, or to the side of the one or more magnets 135. The waveguide 105 can be above, below, or to the side of the plurality of rings 115.

[0055] FIG. 1B illustrates the device 100. The device 100 can include a magneto-optic add-drop memory cell. The device 100 can include the electromagnet 130. The device 100 is an example used to demonstrate magneto-optic memory cells where both counter-propagating modes are excited in the MRR. FIG. 1C illustrates the device 100. The device 100 can include a magneto-optic all-pass memory cell. The device 100 can include the electromagnet 130. The device 100 is an example used to demonstrate magneto-optic memory cells where both counter-propagating modes are excited in the MRR.

[0056] Integration of the Ce:YIG layer with the photonic circuit was achieved through wafer bonding and polishing or by deposition and patterning of an amorphous silicon layer as illustrated in FIGS. 1D and 1E. FIG. 1D illustrates a cross-section of a non-reciprocal memory cell (e.g., device 100). The device 100 can be produced using wafer bonding to a silicon-on-insulator. The device 100 can include the electromagnet 130, the magnet 135, the layer 120, the waveguide 105, and/or the plurality of rings 115. FIG. 1E illustrates a cross-section of a non-reciprocal memory cell (e.g., device 100). The device 100 can include the electromagnet 130, the magnet 135, the layer 120, the waveguide 105, and/or the plurality of rings 115. The device 100 can include the waveguide 105 on YIG or Ce:YIG. Either wafer bonding and chemical mechanical polishing (FIG. 1D) or growth and patterning of amorphous silicon on Ce:YIG substrates (FIG. 1E) was used to heterogeneously integrate Ce:YIG with silicon waveguides. In both cases, high-quality Ce:YIG was achieved by growing the garnet on a native substrate of substituted gadolinium gallium garnet (SGGG). Programming the state of the memory cell can require a radial in-plane magnetic field which can be supplied by an integrated Au

electromagnet. To maintain a non-volatile state without dissipating power, a ferroelectric thin-film (e.g., CoFeB) patterned into an array of bar magnets was integrated with the electromagnet on-chip.

[0057] FIG. 1F shows example spectra from a non-reciprocal memory cell under a negative radial applied magnetic field. FIG. 1G shows example spectra from a non-reciprocal memory cell under a positive (e.g., right) radial applied magnetic field. FIGS. 1F and 1G illustrate positive and negative weights encoded by switching the magnetization direction and amplitude which results in opposite resonance shifts for the clockwise (CW) and counterclockwise (CCW) counter-propagating modes. In the case of positive magnetization ($M_x > 0$), the forward propagating CCW mode (e.g., same propagation direction as current flow in the electromagnet) red shifts while the CW mode (e.g., opposite propagation direction as current flow in the electromagnet) blue shifts. If the optical probe is red detuned from resonance when $M_x = 0$, the resulting differential transmission can encode a negative weight. The opposite can be true for negative magnetization ($M_x < 0$). For a critically coupled MRR, this approach can achieve high transmission contrast. The extinction ratio of the CW and CCW modes may limit the contrast.

[0058] FIG. 1H illustrates the device 100. The device 100 can include the one or more segments 110 of the waveguide 105, the plurality of rings 115, the layer 120, and the one or more magnets 135. The layer 120 can be disposed on top of the one or more segments 110 of the waveguide 105. The layer 120 can be coupled with the one or more segments 110 of the waveguide 105. The layer 120 can be disposed on top of the plurality of rings 115. The layer 120 can be coupled with the plurality of rings 115. The layer 120 can be disposed between the one or more segments 110 of the waveguide 105 and the one or more magnets 135. The layer 120 can be disposed between the plurality of rings 115 and the one or more magnets 135. The one or more magnets 135 can be disposed on top of the layer 120.

[0059] The device 100 can have an ultra-high cycling endurance. For example, the device 100 can have a cycling endurance of at least 2.4 billion write and erase cycles. The device 100 can have a cycling endurance of greater than 1000 write and erase cycles. The device 100 can have a cycling endurance of greater than 1 million write and erase cycles. An arbitrary function generator can be programmed to cycle between write and erase pulses at a rate of 10 kHz, with

an amplitude of ± 5 V and a pulse width of 500 ns. After 2.4 billion write and erase cycles, the device 100 can continue to function without any sign of degradation. This can be greater than three orders of magnitude over other photonic memory technologies, which highlights the benefit of using optically coupled magnetic media for non-volatile data storage. Opto-electronic packaging with active thermal control can counter drive of the MRR resonance peak, which can address a variation in the extinction ratio. The device 100 can offer an efficient non-volatile storage solution that can provide unlimited read/write endurance at sub-nanosecond programming speeds. The device 100 can use integrated electromagnets to switch a non-volatile ferromagnetic (e.g., CoFeB) layer. The device 100 can employ spin-orbit-torque or spin-torque-transfer effects to increase switching efficiency and provide a direct optical interface to magnetic and spintronic memory technologies.

[0060] The functionality of the non-reciprocal memory cell can be extended beyond the single dot-product shown in FIG. 1A to matrix-vector multiplication (MVM) operations. FIG. 2A illustrates a broadcast and weight architecture design featuring non-reciprocal MMR-based weights. FIG. 2B illustrates a detailed view of the microring resonator shown in FIG. 2A. The microring resonator can include a non-reciprocal add-drop microring resonator. FIG. 2C illustrates non-reciprocal weight tuning.

[0061] FIG. 2D illustrates a broadcast and weight architecture design featuring reciprocal MMR-based weights. FIG. 2E illustrates a detailed view of the microring resonator shown in FIG. 2D. The microring resonator can include a reciprocal add-drop microring resonator. FIG. 2F illustrates reciprocal weight tuning.

[0062] FIGS. 2A and 2B illustrate a non-reciprocal photonic computing platform leveraging an integrated magneto-optic memory array. Matrix-vector multiplication was achieved by taking the differential transmission between the clockwise and counterclockwise propagating modes. FIGS. 2D and 2E illustrate a reciprocal broadcast and weight architecture which uses the difference between the through and drop ports of an add-drop microring resonator to encode the values of matrix $\mathbf{W}$. The matrix operation $\mathbf{W}\vec{x} = \vec{b}$ was achieved through fan-out of the optical input vector to each row of $\mathbf{W}$. A distinction between the two approaches can be visualized in the transmission spectra of the bus waveguides. While the differential photocurrent compares the CW and CCW through ports in FIG. 2A, the differential transmission of the

through and drop ports is used to compute $\vec{b}$ in FIG. 2D. The drop port of the reciprocal MRR weight reaches its maximum extinction ratio at a phase shift of π when the optical probe is centered at resonance. Thus, to achieve high optical contrast between the through and drop ports (e.g., to improve bit-precision of the weight), a much larger phase shift was needed in the case of a reciprocal MRR compared to a non-reciprocal MRR. While this may not be a limiting factor for a single memory cell, reducing the phase shift required to achieve the full range of positive and negative weight values in the array reduces crosstalk between neighboring resonances and alleviates the challenge of achieving strong optical modulation on-chip.

[0063] This distinction is highlighted in FIGS. 2G-2J where the differential transmission of both reciprocal and non-reciprocal optical memory with the same quality factor ($Q = 10,000$) are simulated. FIG. 2G illustrates a simulated map of differential through-port transmission for a non-reciprocal memory cell with $Q = 10,000$. In FIG. 2G, the differential transmission for both positive and negative values was an anti-symmetric function centered at $\varphi = 0$. This function is shown in FIG. 2H for three different optical probe wavelengths: $0.5\times$, $1.0\times$, and $1.5\times$ full-width half maximum (FWHM) linewidths red detuned from resonance when $\varphi = 0$. As the detuning of the probe increases, the maximum and minimum weight values increased in magnitude, while the linearity of the weighting function near $\varphi = 0$ decreased. FIG. 2H illustrates the encoded weight value of a non-reciprocal memory cell for an optical probe spaced 0.5 , 1.0 , and 1.5 FWHM away from resonance (dashed lines in FIG. 2G). The encoded value is an anti-symmetric function centered at zero phase-shift.

[0064] The differential transmission for the case of a reciprocal memory cell is shown in FIG. 2I. FIG. 2I illustrates a simulated map of the difference between the through and drop ports of a reciprocal memory cell with $Q = 10,000$. The reciprocal weighting function was symmetric and centered at $\varphi = 0$, which could require a resonance shift on the order of about $0.5\times$ FWHM to reach negative values when the probe is centered at resonance (FIG. 2J). FIG. 2J illustrates the encoded weight value of a reciprocal memory cell when the optical probe is held at resonance (dashed line in FIG. 2I). A larger phase shift is needed to achieve symmetric weighting compared to the non-reciprocal case. Thus, to achieve an equal range of positive and negative weights (e.g., minimal power penalty), a phase shift of $\Delta\varphi = 0.17\pi$ can be required for a reciprocal MRR with the same quality factor of $Q = 10,000$.

[0065] The transmission spectra of magneto-optic memory cell was modeled using the transfer matrix method where the effective index of the CW and CCW modes was computed using a finite element method. The resonance of the MMR was controlled through the magnetic field generated by the integrated electromagnet, which also locally raised the device temperature through Joule heating. The magneto-optic and thermo-optic effect altered the effective index of the modes, and their impact was described using a perturbative approach. The modeling results of FIGS. 2A-2J were experimentally verified for a MRR with Ce:YIG ($Q \approx 10,000$) and a gold integrated electromagnet.

[0066] FIG. 3A shows the optical transmission spectra for the fundamental transverse magnetic (TM) CW and CCW propagating modes as a function of applied current. The resonance position of the spectra showed both a linear and quadratic dependence on the applied current corresponding to the magneto-optic and thermo-optic effects, respectively. FIG. 3A illustrates the spectral response of a non-reciprocal magneto-optic memory cell for different fixed currents ($Q \approx 10,000$). Both linear and quadratic resonance shifts were observed due to the magneto-optic and thermo-optic effects, respectively. In FIGS. 3B and 3C, the resonance shifts of the CW and CCW modes were separated into their non-reciprocal (e.g., magneto-optic) and reciprocal (e.g., thermo-optic) components. While the thermo-optic effect red-shifts both CW and CCW spectra, the magneto-optic effect induces shifts in opposite directions for the two modes. For a set current, the thermo-optic shift was estimated as the average shift of the two spectra compared to the case of no current. The magnitude of the magneto-optic shift was assumed to be half of the measured resonance split between the CW and CCW modes. In FIGS. 3B and 3C, the mathematical model can be overlaid with the measurement results, showing an excellent agreement between theory and experiments. FIG. 3B illustrates the magneto-optic spectral shift for the CW and CCW modes. Dashed lines correspond to the analytical model of the expected magneto-optic phase shift excluding thermal effects. FIG. 3C illustrates the thermo-optic phase shift extracted from FIG. 3A due to heating of the electromagnet while a constant current is applied.

[0067] FIG. 3D plots the FWHM linewidth of the resonator for the CW and CCW modes, showing a similar quality factor for both modes. Slight changes in the extinction ratio in FIG. 3A and linewidth in FIG. 3D correspond to a minor wavelength dependence for the coupling between the resonator and bus waveguide. FIG. 3D illustrates the extracted resonance linewidth

as a function of applied current for the CW and CCW modes. Slight changes in the coupling at different wavelengths can cause changes in the quality factor of the MRR.

[0068] In FIG. 3E, the differential optical transmission of the CW and CCW modes are plotted for three different optical probe wavelength positions: $0.5\times$, $1.0\times$, and $1.5\times$ FWHM linewidths red detuned from resonance when $\varphi = 0$ (e.g., no magnetic field). FIG. 3E illustrates the encoded weight for a probe wavelength red detuned $0.5\times$, $1.0\times$, and $1.5\times$ FWHM away from the central resonance when no magnetic field is applied. Compared to the simulated weighting functions for the case of a resonator with similar quality factor (FIG. 2H), there was agreement with the experimental results. Increasing the red detuning of the optical probe can increase the dynamic range of the weight function due to reduced insertion loss while also decreasing the linearity between the maximum and minimum weight values. At larger current values, a deviation from the expected weight value was observed. This can be attributed to the point that for large detuning, the two modes have different FWHM, resulting in a distinct weighting for the two directions. This was due to the minor wavelength dependence for the coupling between the resonator and bus waveguide, which can be mitigated by designing adiabatic couplers or reducing the detuning of the probe wavelength from resonance.

[0069] Having characterized the steady-state response of the non-reciprocal optical memory, high-speed weight updates were demonstrated through characterization of the memory cell's dynamic response. For high-speed characterization beyond approximately 1 MHz, the magneto-optic response dominates while the dynamic thermo-optic response becomes negligible. This can be seen in FIG. 4A where the dynamic optical transmission of a CW probe for two current pulses can be observed at different time scales (1 ms versus 10 ns pulse width). In the case of a slow 1 ms current pulse, the optical transmission included both a blue shift (e.g., increase in transmission) from the fast magneto-optic response and a red shift (e.g., decrease in transmission) from the slow thermo-optic response. For the case of a fast 10 ns current pulse and red detuned probe, the slow decay from the thermal response of the ring disappeared (e.g., rise time of about 50 μ s and fall time of about 92 μ s). The fast magneto-optic response was observed with a rise and fall time of less than 1 ns, and a ferromagnetic resonance of 0.55 GHz. Since the estimated time response of the integrated electromagnet circuit was 6 ps, the ringing observed in the optical response can be attributed to magneto-optic response of the Ce:YIG, resulting in a rise/fall time of 0.95 ns.

[0070] FIG. 4A illustrates a comparison of the dynamic response of thermo-optic and magneto-optic effects demonstrating five orders of magnitude difference in response time. A red detuned CW probe was used for both measurements. From the thermo-optic response, the fall time was 92 μs while the rise time was 50 μs . For high-speed modulation above approximately 1 MHz, the thermo-optic effect was negligible provided the average power dissipated remained constant. The magneto-optic response was fit with a second order response with a natural angular frequency of 3.6 Grad/s and a dimensionless damping factor equal to 0.29. From these results, a rise/fall time of 0.95 ns and a ferromagnetic resonance of 0.55 GHz was estimated.

[0071] Due to the high-speed magneto-optic response and the soft in-plane magnetic axis of the Ce:YIG, the memory cell can be programmed with low energy. FIGS. 4B and 4C show an open eye diagram measured for both the CW and CCW optical probe for 500 Mbps and 1 Gbps modulation speeds. FIGS. 4B and 4C illustrate eye diagrams for clockwise and counterclockwise propagating modes for pseudorandom binary sequence (PRBS) modulation at 500 Mbps (FIG. 4B) and 1 Gbps (FIG. 4C). FIG. 4B shows that for a weight update rate of 500 Mbps (e.g., 2 ns pulse width), an open eye diagram with an extinction ratio as high as 8.3 dB for a programming energy as low as 2.28 pJ can be achieved. Reducing the pulse width to 1 ns and amplitude by 0.5 $\times$, reduced the programming energy to a mere 298 fJ as shown in FIG. 4C. This corresponds to an improvement of about 8 $\times$ in energy efficiency since $E_b = I^2 R \cdot \Delta t + LI^2/2$, where I is the programming current, R is the resistance of the electromagnet ($\sim 1.43 \Omega$), L is the inductance (0.3 nH), and Δt is the duration of the programming pulse. For the non-reciprocal memory cell, significant modulation of the optical signal with a peak voltage as low as ± 21.5 mV for ± 13.8 mA current pulses was achieved. This can represent an extremely low programming voltage which is compatible with the most advanced CMOS nodes.

[0072] In FIGS. 4D and 4E, multi-level optical weighting was demonstrated using a 4-level (2-bit) pulse amplitude modulation (PAM4) programming signal with maximum current amplitude of ± 13.8 mA, corresponding to a record low programming energy of 143 fJ per bit. In these experiments, the transmission of the CW and CCW modes were captured simultaneously using the experimental setup described in FIG. 9. FIG. 4D illustrates the simultaneous measurement of CW and CCW transmission for PAM4 modulation at 500 Mbps. The differential transmitted power between the CW and CCW modes is shown in FIG. 4E where four distinct

transmission levels were observed. This allowed for two positive and two negative optical weights given the 2-bit electrical input. FIG. 4E illustrates a plot of differential optical power between CW and CCW signals, which demonstrate the ability to rapidly update non-reciprocal multi-bit optical weights. Using the high-speed magneto-optic effect, optical weight updates as fast as 1 ns are shown in FIGS. 4F and 4G. FIG. 4F illustrates the simultaneous measurement of CW and CCW transmission for binary modulation (On-Off Keying) at 1 Gbps. FIG. 4G illustrates the differential optical power between CW and CCW signals demonstrating programming speeds up to 1 ns. The maximum programming speed can be limited by the ferromagnetic resonance of the Ce:YIG. The maximum time response was 1 GHz.

[0073] An example method of fabricating the device 100 can be described below. A 500-nm-thick single-crystalline Ce:YIG ($\text{CeY}_2\text{Fe}_5\text{O}_{12}$) was epitaxially grown on a wafer of (111)-oriented (Ca, Mg, Zr)-substituted gadolinium gallium garnet (SGGG) using an RF sputtering method at 750°C. This magneto-optic garnet has a large Faraday rotation of 4800 deg/cm at 1550 nm and was used for all the devices presented herein.

[0074] Devices characterized in FIGS. 3A-3E and FIGS. 4A-4G were fabricated by bonding a Ce:YIG/SGGG on a 220 nm-thick silicon-on-insulator (SOI) wafer with 2 μm buried oxide. The SOI wafer was patterned using a 248 nm ASML 5500 deep-ultraviolet stepper, and dry etched using a Bosch process (Plasma-Therm 770) to form the waveguides and resonators. Patterned SOI and Ce:YIG/SGGG samples were rigorously cleaned, and activated with O_2 plasma (EVG 810). Ce:YIG was directly bonded onto the SOI wafer using a flip-chip bonder (Finetech) and then annealed at 200°C for 6 h under 3 MPa pressure to strengthen the bond. The alignment accuracy is fairly tolerant (approximately 200 μm). After bonding, a 1 μm layer of SiO_2 was sputtered everywhere on the chip as an upper cladding. Next, the SGGG substrate was thinned by mounting the sample against a flat chuck and polishing (Allied Technologies) using a series of increasingly fine lapping films. The thickness of SGGG was monitored using a micrometer and confirmed to be approximately 5 μm with a separate Dektak (Bruker) profilometry measurement. Variation of thickness across the sample was roughly $\pm 1.5 \mu\text{m}$ due to imperfect levelling of the chuck. The patterns for gold coils and contacts were defined on the backside of the SGGG with a 365 nm GCA i-line wafer stepper. Then, 22 nm Ti was deposited as an underlayer, followed by 1.5 μm Au using electron-beam evaporation, and the metal coils

and contacts were released with a lift-off procedure. Finally, the sample was diced and the facets were polished.

[0075] To compute the transfer function of a memory cell, a mathematical model was developed based on the 2.5D electromagnetic mode analysis, including the magneto-optic and thermo-optic effects a perturbation on the effective index. When no current was injected into the electromagnet (e.g., no magnetic field), the electrical permittivity of all the materials in the device was isotropic. Under those conditions, the optical mode of the waveguide shown in FIG. 5A can be computed. FIG. 5A illustrates a cross-section of the device 100 with an integrated Au electromagnet. FIG. 5B illustrates a profile of the transverse magnetic (TM) optical mode in the silicon/Ce:YIG waveguide. The main component of the magnetic field is shown for the TM mode.

[0076] According to the techniques of the present disclosure, injecting a current in the electromagnet produced an in-plane magnetic field and a local variation of the temperature (e.g., Joule heating), resulting in a phase change of the optical mode. Two contributions of the phase variation can be distinguished, namely, a reciprocal term that depends on the temperature (e.g., thermo-optic effect), and a nonreciprocal one that depends on the magnetic field (e.g., magneto-optic effect). The effective index of the mode can be written as Equation (1):

$$n_{\text{eff}} = n_{\text{eff}}^0 + \Delta n_{\text{TO}} + \Delta n_{\text{MO}} \quad (1)$$

where n_{eff}^0 is the effective index of the mode in the unperturbed case, Δn_{TO} is the variation of the effective index induced by the temperature, and Δn_{MO} is the variation produced by the magnetic field in the MO material.

[0077] The thermo-optic phase shift was computed by combining the results of a multi-physics simulation software with the outcomes of the mode analysis. The variation of the effective index of the mode with respect to the temperature is calculated with the following expression, Equation (2):

$$\begin{aligned}
\Delta n_{TO} &= \frac{dn_{\text{eff}}}{dT} \Delta T \\
&= \left[\frac{dn_{\text{eff}}}{dn_{\text{Si}}} \frac{dn_{\text{Si}}}{dT} + \frac{dn_{\text{eff}}}{dn_{\text{SiO}_2}} \frac{dn_{\text{SiO}_2}}{dT} + \frac{dn_{\text{eff}}}{dn_{\text{CeYIG}}} \frac{dn_{\text{CeYIG}}}{dT} \right. \\
&\quad \left. + \frac{dn_{\text{eff}}}{dn_{\text{Air}}} \frac{dn_{\text{Air}}}{dT} \right] \Delta T
\end{aligned} \tag{2}$$

where dn_i/dT is the thermo-optic coefficient of the material ($i=\text{Si}$, SiO_2 , Ce:YIG and air), while dn_{eff}/dn_i is a function of the waveguide geometry and are computed using the mode analysis. The temperature variation was computed using COMSOL Multiphysics. It is almost constant in the area that overlaps 99% of the optical mode.

[0078] The phase shift induced by the magnetic field (e.g., non-reciprocal effect) was obtained by combining the magnetic field generated by the electromagnet and computed with COMSOL with the results of an electromagnetic mode solver for magneto-optic waveguides.

[0079] At the optical frequencies, the electrical permittivity of a magneto-optic (MO) material can be modified by the magnetic field produced by the electromagnet. The magnetic field was directed along the x-axis (FIGS. 5A and 5B), such that the permittivity tensor of the Ce:YIG above the silicon waveguide becomes:

$$\epsilon_r = \begin{pmatrix} \epsilon_{xx} & 0 & 0 \\ 0 & \epsilon_{yy} & j\epsilon_{yz} \\ 0 & -j\epsilon_{yz} & \epsilon_{zz} \end{pmatrix} \tag{3}$$

where $\epsilon_{xx} = \epsilon_{yy} = \epsilon_{zz} = n_{\text{Ce:YIG}}^2$ and $n_{\text{Ce:YIG}}$ is the optical refractive index of the Ce:YIG . The presence of an external magnetic field can be responsible of the off-diagonal terms ϵ_{yz} , which induce a non-reciprocal phase shift (NRPS) only for the transverse magnetic (TM) mode, while the transverse electric (TE) mode remains unaffected.

[0080] When the in-plane magnetic field was larger than 50 Oe (5 mT), the magnetization of the Ce:YIG saturated and the off-diagonal entries are related to the Faraday rotation constant θ_F^0 by the following expression, Equation (4):

$$\epsilon_{yz} = \frac{2n_{\text{Ce:YIG}}\theta_F^0}{k_0} \tag{4}$$

where k_0 is the propagation constant (or the wavenumber) in the vacuum.

[0081] Under this condition, the effective index of the TM optical mode was computed to be in the range between 1540 nm and 1560 nm, which is shown in FIG. 6. As observed from the numerical results, the effective index for the forward propagating mode, n_{eff}^+ , and the backpropagating mode, n_{eff}^- , results differentiated. As a reference, n_{eff} , which is the value of the effective index in the case when the term ε_{yz} are null, is plotted. FIG. 6 illustrates the effective index of the TM mode versus wavelength. When no magnetic field is applied, the effective index was 2.177 at 1550 nm. Above magnetic saturation, it changed by $\pm 5.66 \cdot 10^{-4}$ with respect to the two directions. The group index ($n_g = 3.199$) did not change significantly among the three cases.

[0082] The geometry that maximizes the non-reciprocal phase shift (NRPS) effect for the TM mode used a 600 nm wide and 220 nm tall silicon waveguide with a 400 nm thick Ce:YIG on top. The mode analysis shown in FIGS. 5A and 5B and the effective indices in FIG. 6 refer to this case. In the mode analysis, a 10-nm oxide layer between the silicon waveguide and the Ce:YIG was included. This layer was a byproduct of the bonding process and reduces the largest NRPS achievable in this geometry.

[0083] Below magnetic saturation (e.g., less than 50 Oe), the Faraday rotation did not reach its largest value and the effective index variation due to the magneto-optic effect decreased. With the off-diagonal terms being small when compared to the diagonal entries of the permittivity tensor, a linear approximation shown in Equation (5) was used:

$$\Delta n_{\text{MO}} = \Delta n_{\text{MO}}^{\text{sat}} \frac{\theta_F}{\theta_F^0} \quad (5)$$

where $\Delta n_{\text{MO}}^{\text{sat}}$ is the largest refractive index variation when the Ce:YIG is magnetically saturated, and θ_F is the Faraday rotation measured below saturation. The value of θ_F can increase linearly with the magnetic field until it reaches a saturation value, while it can decrease linearly when the temperature rises.

[0084] A model is shown in Equation (6):

$$\theta_F(H_x, T) = \left[\theta_F^0 + \frac{d\theta_F}{dT} (T - T_{\text{amb}}) \right] \cdot \tanh \frac{H_x}{H_x^0} \quad (6)$$

where H_x is the in-plane magnetic field, H_x^0 is a constant, T is temperature, T_{amb} is the ambient temperature, and θ_F^0 is the Faraday rotation constant at room temperature when the material is

saturated. For the Ce:YIG, the value of the constants in Equation (6) are $\theta_F^0 = -4500^\circ/\text{cm}$, $H_x^0 = 24 \text{ Oe}$, $d\theta_F/dT = 44^\circ/\text{K} \cdot \text{cm}$.

[0085] Using the COMSOL Multiphysics software, the local heat and the in-plane magnetic field at the silicon/Ce:YIG waveguide were simulated. The corresponding results are shown in FIGS. 7A and 7B. By integrating these outcomes with the model outlined above, the variations of the effective index resulting from the thermo-optic and magneto-optic effects were calculated as a function of the current applied to the electromagnet. The corresponding variation of the effective index are shown in FIGS. 7C and 7D.

[0086] FIG. 7A illustrates temperature variation produced by the electrical current in the integrated electromagnet. FIG. 7B illustrates the in-plane magnetic field produced by the electrical current in the integrated electromagnet. FIG. 7C illustrates refractive index variation due to the thermo-optic. FIG. 7D illustrates the magneto-optic effect. The dotted lines show the maximum achievable NRPS in the case in which there is no local heating.

[0087] The refractive index variation for both the thermo-optic and magneto-optic effects was computed for both forward and backward propagating modes. The thermo-optic effect can be reciprocal, affecting the propagating and counter-propagating modes in the same manner. Since the local heating reduces the maximum NRPS, the maximum achievable magneto-optic refractive index variation in the scenario where no thermal heat is produced (e.g., with a permanent magnet) was reported.

[0088] The input-output transfer function was computed using the effective index for the two propagating directions. The transfer function for the case of an all-pass microring is shown in Equation (7):

$$T^\pm(\lambda, I) = e^{i(\pi+\phi^\pm)} \frac{a - r e^{-i\phi^\pm}}{1 - r a e^{-i\phi^\pm}} \quad (7)$$

where $\phi^\pm = n_{\text{eff}}^\pm(\lambda) k_0 L$ is the single-pass for the CW [$n_{\text{eff}}^+(\lambda)$] and CCW [$n_{\text{eff}}^-(\lambda)$] mode in the microring, with L being the round-trip length (e.g., the microring circumference). The constant $a = e^{-\alpha L}$ is the single-pass field amplitude transmission where α is the field propagation loss. In the case under investigation, CW and CCW modes had the same α , which is 22 dB/cm. The coefficient r is the field transmission coefficient at the microring-bus section. If K is the power

coupling ration, $r = \sqrt{1 - K}$. The amplitude of the transfer functions for the CW and CCW modes are plotted in FIG. 8A. The phase of the transfer functions for the CW and CCW modes are plotted in FIG. 8B. As a reference, the case of no magnetic field is plotted. FIG. 8A illustrates the amplitude of the transfer function for the CW mode $[n_{eff}^+(\lambda)]$ and CCW mode $[n_{eff}^-(\lambda)]$ in the microring when the current in the electromagnet is set to 100 mA. FIG. 8B illustrates the phase of the transfer function for the CW mode $[n_{eff}^+(\lambda)]$ and CCW mode $[n_{eff}^-(\lambda)]$ in the microring when the current in the electromagnet is set to 100 mA. The case with no current is also shown for reference $[n_{eff}(\lambda)]$.

[0089] In Equation (7), the dependence of the transfer function on the wavelength, λ , and electrical current in the electromagnet, I , which generates the magnetic field and local heating, are emphasized. The encoded weight shown in FIG. 2H and FIG. 3E are defined as Equation (8):

$$w(\lambda, I) = T^-(\lambda, I) - T^+(\lambda, I) \quad (8)$$

[0090] The measurement setup used to characterize the dynamic behavior of the magneto-optic memory cell is provided below. The setup configuration is shown schematically in FIG. 9. FIG. 9 illustrates the measurement set-up for high-speed characterization. The set-up can include a digital communications analyzer 905 and an optical probe 910. The laser light, emitted from a tunable laser source (Keysight 81608A), was divided using a 50:50 directional coupler into two paths and then coupled to the two side of the chip through two lensed fibers. This configuration allows for the simultaneous excitation of the clockwise (CW) and the counterclockwise (CCW) modes of the microring. In each path, a circulator was used to redirect the modulated light from the magneto-optic memory cell to a digital communication analyzer. Because the performance of the device is polarization sensitive, all fiber components in the setup were chosen to be polarization maintaining (e.g., the lensed fibers, the circulators, and the directional coupler). The lensed fibers were carefully oriented to selectively excite only the TM-polarized mode in the waveguides with a polarization extinction ratio larger than 23 dB.

[0091] The CW and CCW modulated signals coming from the chip were amplified using two erbium doped fiber amplifiers (EDFA) with similar performance (Amonics AEDFA-PA-35-B-FA and AEDFA-CL-PA-35-B-FA), and filtered using two tunable optical filters. For the eye diagram measurements, the laser wavelength were held fixed at the full-width at half-maximum

(FWHM) of one of the resonances. The binary modulation (On-Off Keying) at 1 Gbps was generated using an error performance analyzer (Hewlett Packard 70843A), while the 4-level pulse amplitude modulation (PAM4) was produced using an arbitrary waveform generator (Keysight 81180B). The modulated light signals were detected using a digital communication analyzer (Agilent Infiniium DCA-J 86100C).

[0092] The thermo-optic and magneto-optic dynamic responses of the memory cell were characterized using the setup presented above. To accurately estimate the rise and fall times of the responses, the experimental thermo-optic response was fitted with a first-order system, while the magneto-optic response was fitted using a second-order response with two complex conjugate roots.

[0093] To evaluate the dynamic behavior of the thermo-optic response, a square wave was used as an input stimulus with a period of $2 \cdot T_s$ where $T_s = 1$ ms, and a duty-cycle of 50%. The corresponding output is modelled using the following expression, Equation (9):

$$y_{To}(t) = C + A h(t - t_d) + B \left[1 - e^{-\frac{(t-t_d)}{\tau_r}} \right] h(t - t_d) - A h(t - t_d - T_s) - B \left[1 - e^{-\frac{(t-t_d-T_s)}{\tau_f}} \right] h(t - t_d - T_s) \quad (9)$$

where $h(t)$ is the Heaviside step function, and t_d is the time delay of the thermal response. The terms multiplied by A were used to model the magneto-optic response, which is instantaneous with respect to the time-scale of the thermal response. The terms multiplied by B reproduced the thermal response, where τ_r and τ_f are the rise and fall times, respectively. The last term C was included to account for bias in the response.

[0094] The experimental results were fitted using a nonlinear least-squares curve-fitting algorithm implemented in MATLAB. Five terms were used as free parameters: A, B and C, and the rise and fall time constants, τ_r and τ_f . From the fitting, it was estimated that $\tau_f = 92$ μ s and $\tau_r = 50$ μ s.

[0095] Similar to the previous case, the device was driven with a square wave having a period $2 \cdot T_i$, where $T_i = 10$ ns, and the duty-cycle is equal to 50%. For fitting the magneto-optic response, a second-order response was used to account for both the initial oscillatory behavior and the damping, Equation (10):

$$y_{MO}(t) = D + E[1 - e^{-\zeta\omega_n(t-t_d)}]\cos(\omega_n\sqrt{1-\zeta^2}(t-t_d))h(t-t_d) - E[1 - e^{-\zeta\omega_n(t-t_d-T_f)}]\cos(\omega_n\sqrt{1-\zeta^2}(t-t_d-T_f))h(t-t_d-T_f) \quad (10)$$

[0096] In Equation (10), the terms multiplied by E reproduce the dynamic magneto-optic response, where ω_n is the natural angular frequency, ζ is the dimensionless damping factor. The terms ω_n and ζ are related to the response of the magneto-optic material. The rise/fall time is given by $(\zeta\omega_n)^{-1}$ while the frequency actually observed in the system is the damped natural frequency $\omega_n\sqrt{1-\zeta^2}$, which is the precession of the magnetic moment in the material called Larmor precession frequency or ferromagnetic resonance. Differently from the thermo-optic response, no differences between the rise and fall time were assumed. As before, the term D is included to account for bias in the response.

[0097] The value of $\omega_n = 3.6$ Grad/s and $\zeta = 0.29$ were obtained fitting the experimental curve using 4 free parameters (i.e., D, E, ω_n and ζ). Using this result, a rise/fall time equal to 0.95 ns was estimated, while the Larmor precession frequency (e.g., the damped natural frequency of the second order system) is equal to 0.55 GHz.

[0098] The results of the fitting indicate that the magneto-optic response of the device is limited by the Ce:YIG and not by the driving circuit. The rise/fall time estimated from the fitting is larger than the time response of the RL circuit, which was estimated from the electrical characterization of the electromagnet. Specifically, by measuring the electrical back-reflection (S_{11} coefficient) of the Au coil, $R = 1.43 \Omega$ and $L = 0.3$ nH. Considering the impedance of the driver is $Z = 50 \Omega$, the response time of the RL circuit is $\tau_c = L/(R + Z) = 5.8$ ps.

[0099] Although the time response of this device was limited to 1 GHz, a much faster response can be accomplished with other magneto-optic materials. For instance, cadmium manganese telluride ($\text{Cd}_{1-x}\text{Mn}_x\text{Te}$) can support a modulation rate of tens of gigahertz.

[0100] The systems and methods of the present disclosure can realize a non-volatile magneto-optical memory cell which features non-reciprocity for in-memory computing in the optical domain. The unique combination of fast, fatigue-free programmability with non-volatile weights addresses limitations of other integrated approaches to optical memory which have yet to combine (1) non-volatility, (2) multi-bit storage, (3) high switching speed, (4) low switching

energy, and (5) high endurance in a single platform. Additionally, leveraging the inherent non-reciprocity of the magneto-optic effect in Ce:YIG can allow symmetric and high contrast encoding of both positive and negative optical weights, alleviating the constraints of amplitude-only weight encoding. Integrated electromagnets, spin-orbit-torque (SOT), and/or spin-torque-transfer (STT) effects can be used to switch a non-volatile ferromagnetic layer. Non-volatile weights can be achieved through the ferromagnetic layer, which can be switched through an integrated electromagnet or spin-orbit-torque effects. Magnetic-based memory can have higher cycling endurance and long-term stability and retention compared to charge trapping, mechanical actuation, phase-change materials, and other non-volatile electrical and optical memory technologies. The systems and methods of the present disclosure can be suitable for photonic computing applications that use multi-level non-volatile storage.

[0101] FIG. 10 illustrates a flow chart of an example method 1000 of managing data. The method 1000 can manage data using a device having a plurality of rings. The plurality of rings can be coupled with a layer. The layer can include a magneto-optic material. The magneto-optic material can exhibit a non-reciprocal phase shift. The method 1000 can include generating a magnetic field (step 1005). The method 1000 can include modifying a plurality of magnetic moments (step 1010). The method 1000 can include passing first light through a first segment of a waveguide (step 1015). The method 1000 can include passing second light through a second segment of the waveguide (step 1020). The method 1000 can include receiving the first light and the second light (step 1025).

[0102] In further detail, the method 1000 can include generating a magnetic field (step 1005). For example, an electromagnet can generate the magnetic field. The electromagnet can include a magnet in which the magnetic field is produced by an electric current. The electromagnet can include an electrically conductive material, such as gold. The electromagnet can have substantially the same shape as the ring. The electromagnet can include a loop conductor and two terminals.

[0103] The method 1000 can include modifying a plurality of magnetic moments (step 1010). The plurality of magnetic moments of the one or more magnets can be modified. For example, the magnetic field from the electromagnet can modify the plurality of magnetic moments of the one or more magnets. The plurality of magnetic moments can be modified by the

magnetic field. An external magnetic field can modify the plurality of magnetic moments of the one or more magnets. Modifying the plurality of magnetic moments of the one or more magnets can include changing one or more of the magnetic strength or orientation of the plurality of magnetic moments of the one or more magnets.

[0104] The method 1000 can include passing first light through a first segment of a waveguide (step 1015). The waveguide can guide the first light through the first segment of the waveguide. The waveguide can guide the first light through the first segment of the waveguide proximate to the plurality of rings. The plurality of rings can each be configured to be excited in the clockwise propagating mode. The first light can excite the clockwise propagating mode in the plurality of rings. Portions of the first light can excite individual rings of the plurality of rings. For example, a first portion of the first light can excite a first ring of the plurality of rings. The first portion of the first light can have a first wavelength. A second portion of the first light can excite a second ring of the plurality of rings. The second portion of the first light can have a second wavelength. A third portion of the first light can excite a third ring of the plurality of rings. The third portion of the first light can have a third wavelength. A fourth portion of the first light can excite a fourth ring of the plurality of rings. The fourth portion of the first light can have a fourth wavelength.

[0105] The method 1000 can include passing second light through a second segment of the waveguide (step 1020). The first segment and the second segment can be separated by a distance. The first segment and the second segment can be substantially parallel. The waveguide 105 can guide the second light through the first segment of the waveguide. The waveguide can guide the second light through the second segment of the waveguide proximate to the plurality of rings. The plurality of rings can each be configured to be excited in the counterclockwise propagating mode. The second light can excite the counterclockwise propagating mode in the plurality of rings. Portions of the second light can excite individual rings of the plurality of rings. For example, a first portion of the second light can excite the first ring of the plurality of rings. The first portion of the second light can have the first wavelength. A second portion of the second light can excite the second ring of the plurality of rings. The second portion of the second light can have the second wavelength. A third portion of the second light can excite the third ring of the plurality of rings. The third portion of the second light can have the third wavelength. A fourth portion of the second light can excite the fourth ring of the plurality of rings. The fourth

portion of the second light can have the fourth wavelength. The first light and the second light can induce a non-reciprocal phase shift for the two counter-propagating modes.

[0106] The method 1000 can include receiving the first light and the second light (step 1025). The analyzer can receive first light from the first segment. For example, the analyzer can receive the portions of the first light after the first light has been modified by the plurality of rings. The analyzer can receive the first portion of the first light, the second portion of the first light, the third portion of the first light, and the fourth portion of the first light after each of the portions of light have been modified by the plurality of rings.

[0107] The method 1000 can include adjusting (e.g., reconfiguring, altering, modifying) the plurality of magnetic moments of the one or more magnets subsequent to receiving, by the analyzer, the first light and the second light. For example, the plurality of magnetic moments of the one or more magnets can be modified subsequent to receiving, by the analyzer, the first light and the second light. This can correspond to rewriting the memory stored on the one or more magnets.

[0108] The method 1000 can include outputting a plurality of spectra corresponding to a plurality of optical weights. The plurality of spectra can include the phase shift and/or resonance split. For example, the plurality of spectra can include the resonance split between the clockwise propagating mode and the counterclockwise propagating mode for each of the plurality of rings. The resonance split can correspond to $-2\Delta\lambda_{MO}$ or $+2\Delta\lambda_{MO}$. The resonance split can be used to encode positive and/or negative weights. $-2\Delta\lambda_{MO}$ can correspond to a negative weight. $+2\Delta\lambda_{MO}$ can correspond to a positive weight.

[0109] FIG. 11 illustrates a flow chart of an example method 1100 of sensing an external magnetic field. The method 1100 can sense an external magnetic field using a device having a plurality of rings. The plurality of rings can be coupled with a layer. The layer can include a magneto-optic material. The magneto-optic material can exhibit a non-reciprocal phase shift. In brief overview, the method 1100 can include passing first light through a first segment of a waveguide (step 1105). The method 1100 can include passing second light through a second segment of the waveguide (step 1110). The method 1100 can include receiving the first light and the second light (step 1115).

[0110] In further detail, the method 1100 can include passing first light through a first segment of a waveguide (step 1105). The waveguide can guide the first light through the first segment of the waveguide. The waveguide can guide the first light through the first segment of the waveguide proximate to the plurality of rings. The plurality of rings can each be configured to be excited in the clockwise propagating mode. The first light can excite the clockwise propagating mode in the plurality of rings. Portions of the first light can excite individual rings of the plurality of rings. For example, a first portion of the first light can excite a first ring of the plurality of rings. The first portion of the first light can have a first wavelength. A second portion of the first light can excite a second ring of the plurality of rings. The second portion of the first light can have a second wavelength. A third portion of the first light can excite a third ring of the plurality of rings. The third portion of the first light can have a third wavelength. A fourth portion of the first light can excite a fourth ring of the plurality of rings. The fourth portion of the first light can have a fourth wavelength.

[0111] The method 1100 can include passing second light through a second segment of the waveguide (step 1110). The first segment and the second segment can be separated by a distance. The first segment and the second segment can be substantially parallel. The waveguide 105 can guide the second light through the first segment of the waveguide. The waveguide can guide the second light through the second segment of the waveguide proximate to the plurality of rings. The plurality of rings can each be configured to be excited in the counterclockwise propagating mode. The second light can excite the counterclockwise propagating mode in the plurality of rings. Portions of the second light can excite individual rings of the plurality of rings. For example, a first portion of the second light can excite the first ring of the plurality of rings. The first portion of the second light can have the first wavelength, and a second portion of the second light can excite the second ring of the plurality of rings. The second portion of the second light can have the second wavelength. A third portion of the second light can excite the third ring of the plurality of rings. The third portion of the second light can have the third wavelength. A fourth portion of the second light can excite the fourth ring of the plurality of rings. The fourth portion of the second light can have the fourth wavelength. The first light and the second light can induce a non-reciprocal phase shift for the two counter-propagating modes.

[0112] The method 1100 can include receiving the first light and the second light (step 1115). The analyzer can receive first light from the first segment. For example, the analyzer can

receive the portions of the first light after the first light has been modified by the plurality of rings. The analyzer can receive the first portion of the first light, the second portion of the first light, the third portion of the first light, and the fourth portion of the first light after each of the portions of light have been modified by the plurality of rings.

[0113] The method 1100 can include shielding a portion of each of the plurality of rings from the external magnetic field. A portion of each of the plurality of rings can be shielded from the external magnetic field. For example, the portion of each of the plurality of rings can be covered or protected from the external magnetic field. The plurality of rings can be partially covered.

[0114] The method 1100 can include outputting a plurality of spectra corresponding to a plurality of optical weights. The plurality of spectra can include the phase shift and/or resonance split. For example, the plurality of spectra can include the resonance split between the clockwise propagating mode and the counterclockwise propagating mode for each of the plurality of rings. The resonance split can correspond to $-2\Delta\lambda_{MO}$ or $+2\Delta\lambda_{MO}$. The resonance split can be used to encode positive and/or negative weights. $-2\Delta\lambda_{MO}$ can correspond to a negative weight. $+2\Delta\lambda_{MO}$ can correspond to a positive weight.

III. Definitions & Terminology

[0115] Directional terms as used herein—for example up, above, below, down, right, left, front, back, top, bottom, vertical, horizontal—are made only with reference to the figures as drawn and are not intended to imply absolute orientation unless otherwise expressly stated.

[0116] Unless otherwise expressly stated, it is in no way intended that any method set forth herein be construed as requiring that its steps be performed in a specific order, nor that with any apparatus specific orientations be required. Accordingly, where a method claim does not actually recite an order to be followed by its steps, or that any apparatus claim does not actually recite an order or orientation to individual components, or it is not otherwise specifically stated in the claims or description that the steps are to be limited to a specific order, or that a specific order or orientation to components of an apparatus is not recited, it is in no way intended that an order or orientation be inferred, in any respect. This holds for any possible non-express basis for interpretation, including operational flow, order of components, or orientation of components;

plain meaning derived from grammatical organization or punctuation, and; the number or type of embodiments described in the specification.

[0117] As used herein, the singular forms “a,” “an” and “the” include plural referents unless the context clearly dictates otherwise. Thus, for example, reference to “a” component includes aspects having two or more such components, unless the context clearly indicates otherwise. Also, the word “or” when used without a preceding “either” (or other similar language indicating that “or” is unequivocally meant to be exclusive – e.g., only one of x or y, etc.) shall be interpreted to be inclusive (e.g., “x or y” means one or both x or y).

[0118] The term “and/or” shall also be interpreted to be inclusive (e.g., “x and/or y” means one or both x or y). In situations where “and/or” or “or” are used as a conjunction for a group of three or more items, the group should be interpreted to include one item alone, all the items together, or any combination or number of the items. Moreover, terms used in the specification and claims such as have, having, include, and including should be construed to be synonymous with the terms comprise and comprising. Other elements may optionally be present other than the elements specifically identified by the “and/or” clause, whether related or unrelated to those elements specifically identified. As a non-limiting example, a reference to “X and/or Y” may refer, in one embodiment, to X only (optionally including elements other than Y); in some embodiments, to Y only (optionally including elements other than X); in yet some embodiments, to both X and Y (optionally including other elements).

[0119] The drawings may be interpreted, for example, as showing: (a) everything drawn to scale, (b) nothing drawn to scale, or (c) one or more features drawn to scale and one or more features not drawn to scale. Accordingly, the drawings may serve to provide support to recite the sizes, proportions, and/or other dimensions of any of the illustrated features either alone or relative to each other. Furthermore, all such sizes, proportions, and/or other dimensions are to be understood as being variable from 0-100% in either direction and thus provide support for claims that recite such values or any and all ranges or subranges that may be formed by such values.

[0120] References to specific examples, use of “i.e.,” use of the word “invention,” etc., are not meant to invoke exception (b) or otherwise restrict the scope of the recited claim terms. Other than situations where exception (b) applies, nothing contained in this document should be considered a disclaimer or disavowal of claim scope.

[0121] Unless the context indicates otherwise, it is specifically intended that the various features of the disclosure described herein may be used in any combination. Moreover, the disclosure also contemplates that in some embodiments, any feature or combination of features set forth herein may be excluded or omitted. To illustrate, if the specification states that a device comprises components A, B and C, any of A, B or C, or a combination thereof, may be omitted and disclaimed singularly or in any combination.

[0122] As used herein, “about” or “approximately” will be understood by persons of ordinary skill in the art and will vary to some extent depending upon the context in which it is used. If there are uses of the term which are not clear to persons of ordinary skill in the art, given the context in which it is used, “about” or “approximately” will mean up to plus or minus 10% of the particular term.

[0123] While certain embodiments have been illustrated and described, it should be understood that changes and modifications may be made therein in accordance with ordinary skill in the art without departing from the technology in its broader aspects as defined in the following claims.

[0124] The embodiments, illustratively described herein may suitably be practiced in the absence of any element or elements, limitation or limitations, not specifically disclosed herein. Thus, for example, the terms “comprising,” “including,” “containing,” etc. shall be read expansively and without limitation. Additionally, the terms and expressions employed herein have been used as terms of description and not of limitation, and there is no intention in the use of such terms and expressions of excluding any equivalents of the features shown and described or portions thereof, but it is recognized that various modifications are possible within the scope of the claimed technology. Additionally, the phrase “consisting essentially of” will be understood to include those elements specifically recited and those additional elements that do not materially affect the basic and novel characteristics of the claimed technology. The phrase “consisting of” excludes any element not specified.

[0125] The present disclosure is not to be limited in terms of the particular embodiments described in this application. Many modifications and variations may be made without departing from its spirit and scope, as will be apparent to those skilled in the art. Functionally equivalent

methods and compositions within the scope of the disclosure, in addition to those enumerated herein, will be apparent to those skilled in the art from the foregoing descriptions. Such modifications and variations are intended to fall within the scope of the appended claims. The present disclosure is to be limited only by the terms of the appended claims, along with the full scope of equivalents to which such claims are entitled. It is to be understood that this disclosure is not limited to particular methods, which may of course vary. It is also to be understood that the terminology used herein is for the purpose of describing particular embodiments only, and is not intended to be limiting.

[0126] As will be understood by one skilled in the art, for any and all purposes, particularly in terms of providing a written description, all ranges disclosed herein also encompass any and all possible subranges and combinations of subranges thereof, inclusive of the endpoints. As such, all disclosed ranges are to be understood to encompass and provide support for claims that recite any and all subranges or any and all individual values subsumed by each range. For example, a stated range of 1 to 10 should be considered to include and provide support for claims that recite any and all subranges or individual values that are between and/or inclusive of the minimum value of 1 and the maximum value of 10; that is, all subranges beginning with a minimum value of 1 or more and ending with a maximum value of 10 or less (e.g., 5.5 to 10, 2.34 to 3.56, and so forth) or any values from 1 to 10 (e.g., 3, 5.8, 9.9994, and so forth).

[0127] Any listed range may be easily recognized as sufficiently describing and enabling the same range being broken down into at least equal halves, thirds, quarters, fifths, tenths, etc. As a non-limiting example, each range discussed herein may be readily broken down into a lower third, middle third and upper third, etc. As will also be understood by one skilled in the art all language such as “up to,” “at least,” “greater than,” “less than,” and the like, include the number recited and refer to ranges which may be subsequently broken down into subranges as discussed above. Further, as will be understood by one skilled in the art, a range includes each individual member. Thus, for example, a group having 1-3 layers refers to groups having 1, 2, or 3 layers. Similarly, a group having 1-5 layers refers to groups having 1, 2, 3, 4, or 5 layers, and so forth.

[0128] Any publications, patent applications, issued patents, and other documents referred to in this specification are herein incorporated by reference as if each individual publication, patent application, issued patent, or other document was specifically and individually indicated to be incorporated by reference in its entirety. Definitions that are contained in text incorporated by reference are excluded to the extent that they contradict definitions in this disclosure.

[0129] Other embodiments are set forth in the following claims.

WHAT IS CLAIMED IS:

1. A device, comprising:
 - a waveguide comprising a first segment and a second segment;
 - a plurality of rings disposed between the first segment and the second segment, the plurality of rings coupled with a layer, the layer comprising a magneto-optic material, the magneto-optic material configured to exhibit a non-reciprocal phase shift; and
 - an analyzer configured to receive first light from the first segment and second light from the second segment.
2. The device of claim 1, further comprising:
 - one or more magnets disposed proximate to each of the plurality of rings, the one or more magnets comprising a ferromagnetic material; and
 - an electromagnet configured to generate a magnetic field to modify a plurality of magnetic moments of the one or more magnets.
3. The device of claim 2, wherein the one or more magnets are configured to encode a plurality of optical weights.
4. The device of claim 2, wherein:
 - the one or more magnets are disposed between the electromagnet and the plurality of rings; and
 - the plurality of rings are disposed between the one or more magnets and the waveguide.
5. The device of claim 2, wherein:
 - the one or more magnets are disposed between the electromagnet and the plurality of rings; and
 - the waveguide is disposed between the one or more magnets and the plurality of rings.
6. The device of claim 2, wherein the one or more magnets comprise CoFeB.

7. The device of claim 1, wherein:

the waveguide is configured to guide the first light through the first segment of the waveguide proximate to the plurality of rings, which are each configured to be excited in a clockwise propagating mode; and

the waveguide is configured to guide the second light through the second segment of the waveguide proximate to the plurality of rings, which are each configured to be excited in a counterclockwise propagating mode.

8. The device of claim 7, wherein the analyzer is configured to detect a resonance split between the clockwise propagating mode and the counterclockwise propagating mode for each of the plurality of rings.

9. The device of claim 1, wherein the magneto-optic material is configured to exhibit the non-reciprocal phase shift due to at least one of light, a current, spin-orbit torque, or a magnetic field.

10. The device of claim 1, wherein the non-reciprocal phase shift of the magneto-optic material comprises a property of the magneto-optic material such that the property has a first value when light passes through the magneto-optic material in a first direction and the property has a second value different from the first value when light passes through the magneto-optic material in a second direction different from the first direction.

11. The device of claim 1, wherein the non-reciprocal phase shift of the magneto-optic material comprises opposite resonance shifts for a clockwise propagating mode and a counterclockwise propagating mode.

12. The device of claim 1, wherein the magneto-optic material comprises cerium yttrium iron garnet.

13. The device of claim 1, wherein the analyzer is configured to determine one or more states of an external magnetic field.

14. The device of claim 13, wherein a portion of each of the plurality of rings is shielded from the external magnetic field.
15. The device of claim 1, wherein the waveguide comprises a y-splitter.
16. The device of claim 1, wherein the device is configured to have a cycling endurance of at least 2.4 billion write and erase cycles.
17. A method of managing data using a device having a plurality of rings coupled with a layer, the layer comprising a magneto-optic material, the magneto-optic material configured to exhibit a non-reciprocal phase shift, the method comprising:
- generating a magnetic field;
 - modifying, by the magnetic field, a plurality of magnetic moments of one or more magnets disposed proximate to each of the plurality of rings, the one or more magnets comprising a ferromagnetic material to store the data corresponding to one or more strengths and one or more directions of the magnetic field;
 - passing first light through a first segment of a waveguide, the waveguide configured to guide the first light through the first segment of the waveguide proximate to the plurality of rings, which are each configured to be excited in a clockwise propagating mode;
 - passing second light through a second segment of the waveguide, the waveguide configured to guide the second light through the second segment of the waveguide proximate to the plurality of rings, which are each configured to be excited in a counterclockwise propagating mode; and
 - receiving, by an analyzer, the first light from the first segment and the second light from the second segment for each of the plurality of rings to retrieve the data from the one or more magnets.
18. The method of claim 17, further comprising:
- adjusting the plurality of magnetic moments of the one or more magnets subsequent to receiving, by the analyzer, the first light and the second light.

19. The method of claim 17, further comprising:
outputting a plurality of spectra corresponding to a plurality of optical weights.
20. The method of claim 17, wherein the data corresponds to one or more optical transmission levels.
21. A method of sensing an external magnetic field using a device having a plurality of rings coupled with a layer, the layer comprising a magneto-optic material, the magneto-optic material configured to exhibit a non-reciprocal phase shift, the method comprising:
passing first light through a first segment of a waveguide, the waveguide configured to guide the first light through the first segment of the waveguide proximate to the plurality of rings, which are each configured to be excited in a clockwise propagating mode;
passing second light through a second segment of the waveguide, the waveguide configured to guide the second light through the second segment of the waveguide proximate to the plurality of rings, which are each configured to be excited in a counterclockwise propagating mode; and
receiving, by an analyzer, the first light from the first segment and the second light from the second segment for each of the plurality of rings.
22. The method of claim 21, further comprising:
shielding a portion of each of the plurality of rings from the external magnetic field.
23. The method of claim 21, further comprising:
outputting a plurality of spectra corresponding to a plurality of optical weights.