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(71) Applicant: INTEL CORPORATION [US/US]; 2200 Mission College Blvd., Santa Clara, California 95054 (US).

(72) Inventors: MANIPATRUNI, Sasikanth; 6993 NE Ronler Way, #1817, Hillsboro, Oregon 97124 (US). NIKONOV, Dmitri E.; 16560 SW Whitetail Lane, Beaverton, Oregon 97007 (US). YOUNG, Ian A.; 3181 NW 114th Avenue, Portland, Oregon 97229 (US).

(74) Agent: MUGHAL, Usman A.; Green, Howard & Mughal, LLP, 5 Centerpointe Dr. Suite 400, Lake Oswego, OR 97035 (US).

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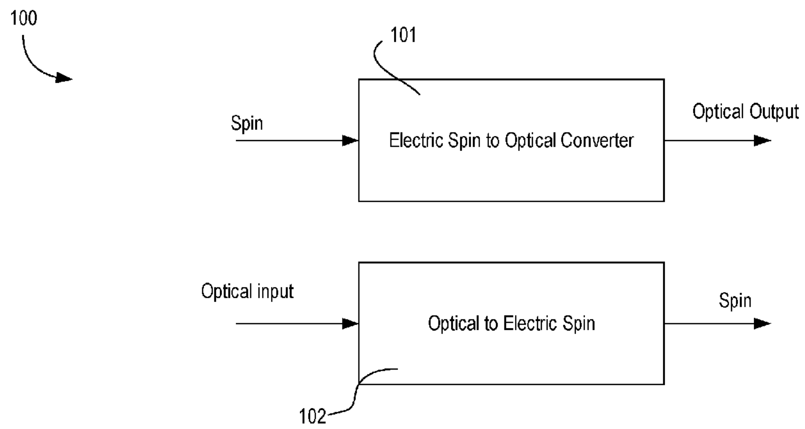

Fig. 1

(57) Abstract: An apparatus is provided which comprises: a waveguide; and a layer of high spin orbit coupling material being adjacent to the waveguide. An apparatus is provided which comprises: a waveguide; a layer high spin orbit coupling material adjacent to the waveguide; a first ferromagnet adjacent to the layer of high spin orbit coupling material; and a second ferromagnet adjacent to the layer of high spin orbit coupling material, wherein the first and second ferromagnets are separated from one another by a distance.

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NANO-LASER FOR SPIN TO OPTICAL AND OPTICAL TO SPIN TRANSDUCTION

BACKGROUND

[0001] Optical signals are routinely converted into electrical signals and vice versa. Another media for carrying information is spin or magnetization related to it. For example, spin of an electron can be used to carry information in a ferromagnet. Spin-transfer torque (STT) based logic devices that use spins and magnets for information processing have been proposed.

BRIEF DESCRIPTION OF THE DRAWINGS

[0002] The embodiments of the disclosure will be understood more fully from the detailed description given below and from the accompanying drawings of various embodiments of the disclosure, which, however, should not be taken to limit the disclosure to the specific embodiments, but are for explanation and understanding only.

[0003] **Fig. 1** illustrates conceptual block diagrams of spin-to-optical and optical-to-spin converters, according to some embodiments of the disclosure.

[0004] **Fig. 2** illustrates spin orbit material integrated optical device with electric input, according to some embodiments of the disclosure.

[0005] **Fig. 3** illustrates spin orbit material integrated optical device with cavity and with electric input, according to some embodiments of the disclosure.

[0006] **Fig. 4** illustrates spin orbit material integrated optical device with cavity and with ferromagnet contacts, according to some embodiments of the disclosure.

[0007] **Fig. 5** illustrates mode selected spin orbit material integrated optical device with cavity and with ferromagnet contacts, according to some embodiments of the disclosure.

[0008] **Fig. 6** illustrates a top view of a one dimensional (1D) photonic crystal cavity spin orbit material spin laser, according to some embodiments of the disclosure.

[0009] **Fig. 7** illustrates a plot showing optical transmittivity over wavelength for spin to optical conversion, according to some embodiments of the disclosure.

[0010] **Fig. 8** illustrates a top view of an enhanced quality factor two-dimensional (2D) photonic crystal cavity spin orbit material spin laser, according to some embodiments of the disclosure.

[0011] **Fig. 9** illustrates a method flowchart of converting spin electrical signal into an optical signal, according to some embodiments of the disclosure.

[0012] **Fig. 10** illustrates a method flowchart of converting an optical signal to spin electrical signal, according to some embodiments of the disclosure.

[0013] **Fig. 11** illustrates a smart device or a computer system or a SoC (System-on-Chip) with a spin-optical transducer(s), according to some embodiments of the disclosure.

DETAILED DESCRIPTION

[0014] All Spin Devices (ASD) and circuits are being actively pursued to identify technology options for the beyond Complementary Metal Oxide Semiconductor (CMOS) era. In this context, a method to interface spin circuits to long range optical interconnects is desired because spin interconnects are limited by spin diffusion dynamics (e.g., 100 times slower, and less than 1 micron spin flip length).

[0015] Some embodiments describe a spin to optical transducer. Some embodiments describe an optical to spin transducer. Some embodiments enable spintronic circuits to directly interface with intra-chip and chip-to-chip interconnect. The transducer of some embodiments is comprised of waveguide or optical cavity formed by light confinement (e.g., by micro ring resonators, one dimensional (1D) photonic crystal cavity and/or two/three dimensional (2D/3D) photonic crystal cavities). In some embodiments, the spin to electrical or optical transduction is realized by spin dependent optical gain and spin dependent optical absorption. In some embodiments, spin dependent optical gain and spin dependent optical absorption is enabled by a class of materials with strong spin orbit coupling. Such materials are referred to as "high spin orbit coupling material" or "spin orbit material" for short. In some embodiments, the transducer comprises an optical device which is coupled to a spin orbit material (e.g., a di-chalcogenide MoS_2). In some embodiments, the transducer comprises electrical contacts that are used to receive spin electrical signal via spin orbit material.

[0016] In the following description, numerous details are discussed to provide a more thorough explanation of embodiments of the present disclosure. It will be apparent, however, to one skilled in the art, that embodiments of the present disclosure may be practiced without these specific details. In other instances, well-known structures and devices are shown in block diagram form, rather than in detail, in order to avoid obscuring embodiments of the present disclosure.

[0017] Note that in the corresponding drawings of the embodiments, signals are represented with lines. Some lines may be thicker, to indicate more constituent signal paths, and/or have arrows at one or more ends, to indicate primary information flow direction. Such indications are not intended to be limiting. Rather, the lines are used in connection with one or more exemplary embodiments to facilitate easier understanding of a circuit or a logical unit. Any represented signal, as dictated by design needs or preferences, may actually comprise one or more signals that may travel in either direction and may be implemented with any suitable type of signal scheme.

[0018] Throughout the specification, and in the claims, the term "connected" means a direct connection, such as electrical, mechanical, or magnetic connection between the things that are connected, without any intermediary devices. The term "coupled" means a direct or indirect connection, such as a direct electrical, mechanical, or magnetic connection between the things that are connected or an indirect connection, through one or more passive or active intermediary devices. The term "circuit" or "module" may refer to one or more passive and/or active components that are arranged to cooperate with one another to provide a desired function. The term "signal" may refer to at least one current signal, voltage signal, magnetic signal, or data/clock signal. The meaning of "a," "an," and "the" include plural references. The meaning of "in" includes "in" and "on."

[0019] The term "scaling" generally refers to converting a design (schematic and layout) from one process technology to another process technology and subsequently being reduced in layout area. The term "scaling" generally also refers to downsizing layout and devices within the same technology node. The term "scaling" may also refer to adjusting (e.g., slowing down or speeding up – i.e. scaling down, or scaling up respectively) of a signal frequency relative to another parameter, for example, power supply level. The terms "substantially," "close," "approximately," "near," and "about," generally refer to being within +/- 10% of a target value.

[0020] Unless otherwise specified the use of the ordinal adjectives "first," "second," and "third," etc., to describe a common object, merely indicate that different instances of like objects are being referred to, and are not intended to imply that the objects so described must be in a given sequence, either temporally, spatially, in ranking or in any other manner.

[0021] For the purposes of the present disclosure, phrases "A and/or B" and "A or B" mean (A), (B), or (A and B). For the purposes of the present disclosure, the phrase "A, B, and/or C" means (A), (B), (C), (A and B), (A and C), (B and C), or (A, B and C). The terms "left," "right," "front," "back," "top," "bottom," "over," "under," and the like in the description and in the claims, if any, are used for descriptive purposes and not necessarily for describing permanent relative positions. For the purposes of present disclosure, the terms "spin" and "magnetic moment" are used equivalently. More rigorously, the direction of the spin is opposite to that of the magnetic moment, and the charge of the particle is negative (such as in the case of electron).

[0022] **Fig. 1** illustrates conceptual block diagrams 100 of spin-to-optical and optical-to-spin converters, according to some embodiments of the disclosure. In some embodiments, transducer 101 is provided which converts spin current into optical output. In some embodiments, transducer 101 realizes the spin to optic transduction by spin dependent optical gain. In some embodiments, transducer 102 is provided which converts optical input into spin. In some embodiments, transducer 102 is realized by spin dependent optical absorption. In some embodiments, the spin orbit material contains a chalcogenide (and in some embodiments, transition metal di-chalcogenide) layer which is formed of a material selected from a group consisting of: graphene, TiS_2, WS_2, MoS_2, $TiSe_2$, WSe_2, $MoSe_2$, B_2S_3, Sb_2S_3, Ta_2S, Re_2S_7, $LaCPS_2$, $LaOAsS_2$, $ScOBiS_2$, $GaOBiS_2$, $AlOBiS_2$, $LaOSbS_2$, $BiOBiS_2$, $YOBiS_2$, $InOBiS_2$, $LaOBiSe_2$, $TiOBiS_2$, $CeOBiS_2$, $PrOBiS_2$, $NdOBiS_2$, $LaOBiS_2$, and $SrFBiS_2$.

[0023] In some embodiments, the functions of transducers 101 and 102 are implemented in the same structure. For example, depending on the applied stimulus, spin-to-optical or optical-to-spin conversion is achieved. In some embodiments, transducers 101/102 comprise a waveguide or an optical cavity formed by light confinement (e.g., by micro ring resonators, one dimensional (1D) photonic crystal cavity and/or two/three dimensional (2D/3D) photonic crystal cavities). In some embodiments, transducers 101/102 comprise an optical device which is coupled to a spin orbit material. In some embodiments, the transducer comprises electrical contacts that are used to receive spin electrical signal via spin orbit material.

[0024] **Fig. 2** illustrates spin orbit material integrated optical device 200 with electric input, according to some embodiments of the disclosure. In some embodiments, device 200 comprises waveguide 201, layer of spin orbit material 202, first electrode 203, and second electrode 204. In some embodiments, waveguide 201 is formed of a material selected from a group consisting of: Si, Ge, SiGe, SiN, doped SiO_2 glass, acrylic or acrylic glass (PMMA), polystyrene, diamond, and elements from the group III through V of the periodic table. In some embodiments, waveguide 201 is comprised in a micro ring resonator.

[0025] In some embodiments, the spin orbit material for layer 202 is selected from a group consisting of: $TiSe_2$, $MoSe_2$, WSe_2, SiS_2, B_2S_3, Sb_2S_3, Ta_2S, Re_2S_7, and semiconductors of the type MX_2, with 'M' being a transition metal atom (e.g., Mo, W, etc.) and 'X' being a chalcogen atom (e.g., S, Se, or Te.). In some embodiments, layer of spin orbit material 202 is formed of a material selected from a group consisting of: graphene, TiS_2,

WS_2, MoS_2, $TiSe_2$, WSe_2, $MoSe_2$, B_2S_3, Sb_2S_3, Ta_2S, Re_2S_7, $LaCPS_2$, $LaOAsS_2$, $ScOBiS_2$, $GaOBiS_2$, $AlOBiS_2$, $LaOSbS_2$, $BiOBiS_2$, $YOBiS_2$, $InOBiS_2$, $LaOBiSe_2$, $TiOBiS_2$, $CeOBiS_2$, $PrOBiS_2$, $NdOBiS_2$, $LaOBiS_2$, and $SrFBiS_2$.

[0026] In some embodiments, layer 202 comprises a material with high spin orbit coupling. In some embodiments, spin orbit material contains one or more of: Tantalum (β-Ta), Ta, β-Tungsten (β-W), W, Pt, Copper (Cu) doped with elements such as Iridium, Bismuth and any of the elements of 3d, 4d, 5d and 4f, 5f periodic groups in the Periodic Table which may exhibit high spin orbit coupling.

[0027] In some embodiments, the layer of spin orbit material 202 belongs to a class of two dimensional (2D) materials. 2D material or layers formed from transition metal di-chalcogenides exhibit high spin orbit coupling, which can produce strong spin to charge and charge to spin conversion. In one example of a di-chalcogenide structure, each sulfur center is pyramidal and is connected to three molybdenum (Mo) centers. In this way, trigonal prisms are interconnected to give a layered structure, wherein molybdenum atoms are sandwiched between layers of sulfur atoms. In some embodiments, the 2D materials are selected from a group consisting of: Graphene, MoS_2, WSe_2, WS_2, $MoSe_2$ with copper, silver, platinum, bismuth, Fluorine, Hydrogen adsorbents. In some embodiments, the 2D materials include extrinsic material such as graphene, MoS_2, WSe_2, WS_2, $MoSe_2$ with Copper, Silver, Platinum, Bismuth, Fluorine, and Hydrogen adsorbents. These adsorbents are intrinsic material which are added on top of the extrinsic material.

[0028] In some embodiments, first electrode 203 is doped with n-doped material, e.g. silicon doped with phosphorous. In some embodiments, first electrode 203 is adjacent to layer of spin orbit material 202. For example, first electrode 203 is in direct contact to layer of spin orbit material 202. In some embodiments, second electrode 204 is doped with p-doped material, e.g. silicon doped with boron. In some embodiments, second electrode 204 is adjacent to the layer of spin orbit material 202. For example, second electrode 204 is in direct contact to the layer of spin orbit material 202.

[0029] In some embodiments, first and second electrodes 203 and 204 are separated from one another. For example, first and second electrodes 203 and 204 are separated by a dielectric or insulator. Any suitable dielectric or insulator can be used. In some embodiments, first and second electrodes 203 and 204 are formed of non-magnetic materials. For example, first and second electrodes 203 and 204 are formed of a material selected from a group consisting of: Cu, Ag, Au, and Al. In some embodiments, first and second electrodes 203 and 204 are formed of high conductivity non-magnetic metal(s) to reduce the resistance when in contact with layer of spin orbit material 202. The non-magnetic metal(s) can be formed from one or more of: Cu, Co, α-Ta, Al, CuSi, or NiSi.

[0030] In some embodiments, to operate device 200 as a spin to optical transducer, a potential voltage is applied across first and second electrodes 203 and 204. The potential difference causes electron to inject into the layer of spin orbit material 202. These electrons become spin polarized because of SOC in the spin orbital material. When voltage is applied across first and second electrodes 203 and 204, holes are also generated. The spin polarized electrons and holes annihilate to produce polarized photons in waveguide 201. These polarized photons are the light output of waveguide 201.

[0031] In some embodiments, to operate device 200 as an optical to spin or electrical transducer, light is injected into waveguide 201. This injected light (i.e., photons) interact with the layer of spin orbit material 202 to generate spin polarized electrons and holes. These spin polarized electrons and holes can have spin-up or spin-down orientations depending on the polarization of the photons in waveguide 201. The spin polarized electrons and holes are then detected via the current they produce between electrodes 203 and 204.

[0032] **Fig. 3** illustrates spin orbit material integrated optical device 300 with cavity and with electric input, according to some embodiments of the disclosure. It is pointed out that those elements of **Fig. 3** having the same reference numbers (or names) as the elements of any other figure can operate or function in any manner similar to that described, but are not limited to such.

[0033] In some embodiments, a cavity is added on one or both sides of waveguide 201. In some embodiments, the cavity is a Bragg reflector which comprises layers 301a/b and 303a/b at one end, and layers 304a/b and 305a/b at another end of waveguide 201. The layer of the Bragg reflector are formed of alternating materials with different refractive index.

[0034] For example, layer 305a has a different refractive index than layer 305b, and layer 304a has a different refractive index than layer 304b. In some embodiments, the refractive index of layers 304a and 304b are the same. In some embodiments, the refractive index of layers 305a and 305b are the same. In some embodiments, layer 301a has a different refractive index than layer 303b, and layer 301b has a different refractive index than layer 303b. In some embodiments, the refractive index of layers 301a and 301b are the same. In some embodiments, the refractive index of layers 303a and 303b are the same. In some embodiments, the alternating layers of the Bragg reflectors have periodic variation of some characteristic (such as height) of a dielectric waveguide, resulting in periodic variation in the effective refractive index in the guide. In some embodiments, each layer of the Bragg reflectors causes a partial reflection of an optical wave. As such, the optical output from section 305 of the waveguide 201 is a coherent light generated from the electron spins in spin orbit material 302.

[0035] In some embodiments, the layer of spin orbit material 302 is formed of a material selected from a group consisting of: graphene, TiS_2, WS_2, MoS_2, $TiSe_2$, WSe_2, $MoSe_2$, B_2S_3, Sb_2S_3, Ta_2S, Re_2S_7, $LaCPS_2$, $LaOAsS_2$, $ScOBiS_2$, $GaOBiS_2$, $AlOBiS_2$, $LaOSbS_2$, $BiOBiS_2$, $YOBiS_2$, $InOBiS_2$, $LaOBiSe_2$, $TiOBiS_2$, $CeOBiS_2$, $PrOBiS_2$, $NdOBiS_2$, $LaOBiS_2$, and $SrFBiS_2$. In some embodiments, the di-chalcogenide material for layer 302 is selected from a group consisting of: $TiSe_2$, $MoSe_2$, WSe_2, SiS_2, B_2S_3, Sb_2S_3, Ta_2S, Re_2S_7, and semiconductors of the type MX_2, with 'M' being a transition metal atom (e.g., Mo, W, etc.) and 'X' being a chalcogen atom (e.g., S, Se, or Te).

[0036] In some embodiments, layer of spin orbit material 302 belongs to the class of 2D materials with high spin orbit coupling. 2D material or layers formed from transition metal di-chalcogenides exhibit high spin orbit coupling, which can produce strong spin to charge and charge to spin conversion. In some embodiments, the 2D materials are selected from a group consisting of: Graphene, MoS_2, WSe_2, WS_2, $MoSe_2$ with copper, silver, platinum, bismuth, Fluorine, Hydrogen adsorbents. In some embodiments, the 2D materials include extrinsic material such as graphene, MoS_2, WSe_2, WS_2, $MoSe_2$ with Copper, Silver, Platinum, Bismuth, Fluorine, and Hydrogen adsorbents. These adsorbents are intrinsic material which are added on top of the extrinsic material.

[0037] In some embodiments, a high density 2D electron gas with high Rashba spin orbit coupling is used to generate spin dependent optical effects in the layer of spin orbit material 302. The spin-orbit mechanism responsible for spin to charge conversion is described by the Rashba effect in 2D electron gases. The Hamiltonian (energy) of spin-orbit coupling electrons in a 2D electron gas is:

$$H_R = \alpha_R(\grave{k} \times \hat{z}).\grave{\sigma}$$

where $\alpha_R$is the Rashba coefficient, '$\grave{k}$' is the operator of momentum of electrons, $\hat{z}$ is a unit vector perpendicular to the 2D electron gas, and $\grave{\sigma}$ is the operator of spin of electrons.

The spin polarized electrons with direction of polarization in-plane (in the xy-plane) experience an effective magnetic field dependent on the spin direction which is given as:

$$B(\grave{k}) = \frac{\alpha_R}{\mu_B}(\grave{k} \times \hat{z})$$

where $\mu_B$is the Bohr's magneton.

[0038] This results in the generation of a charge current in the interconnect proportional to the spin current I_s. The spin orbit interaction (i.e., the Inverse Rashba-Edelstein Effect (IREE)) at the interface of ferromagnet contacts and the layer of spin orbit material 302 produces a charge current I_c in the horizontal direction which is expressed as:

$$I_c = \frac{\lambda_{IREE} I_S}{w_m}$$

where w_m is width of the magnet 403/404, and λ_{IREE} is the IREE constant (with units of length) proportional to α_R.

[0039] The IREE effect produces spin-to-charge current conversion efficiency around 0.1 with existing materials at 10nm magnet width. For scaled nanomagnets (e.g., 5nm width) and exploratory materials such as Bi_2Se_3, the spin-to-charge conversion efficiency can be between 1 and 2.5, in accordance with some embodiments. The net conversion of the drive charge current $I_d$to magnetization dependent charge current is:

$$I_c = \pm \frac{\lambda_{IREE} P I_d}{w_m} \ldots (6)$$

where P is the spin polarization. The spin polarization produces polarized photons when the spin polarized electrons combine with holes. These photons are then collected at one end of waveguide 201, in accordance with some embodiments.

[0040] **Fig. 4** illustrates spin orbit material integrated optical device 400 with cavity and with ferromagnet contacts, according to some embodiments of the disclosure. It is pointed out that those elements of **Fig. 4** having the same reference numbers (or names) as the elements of any other figure can operate or function in any manner similar to that described, but are not limited to such. So as not to obscure the embodiments, differences between device 300 of **Fig. 3** and device 400 of **Fig. 4** are described.

[0041] In some embodiments, instead of non-magnetic first and second electrodes on the layer of spin orbit material 302, first and second magnetic electrodes (or contacts) 403 and 404, respectively, are added on the layer of spin orbit material 302. In some embodiments, a spin logic device provides inputs to the first and second magnetic electrodes (or contacts) 403 and 404, respectively. In other embodiments, other logic stage(s) may provide input to first and second magnetic electrodes (or contacts) 403 and 404, respectively. For example, domain wall logic and/or magneto-electric logic may be used to inject spin currents to spin orbit material 302 via first and second magnetic electrodes (or contacts) 403 and 404, respectively.

[0042] In some embodiments, first and second magnetic electrodes (or contacts) 403 and 404 are formed of CFGG (i.e., Cobalt (Co), Iron (Fe), Germanium (Ge), or Gallium (Ga) or a combination of them). In some embodiments, first and second magnetic electrodes (or contacts) 403 and 404 are formed from Heusler alloys. Heusler alloys are ferromagnetic metal alloys based on a Heusler phase. Heusler phases are intermetallic with certain composition and face-centered cubic crystal structure. The ferromagnetic property of the Heusler alloys are a result of a double-exchange mechanism between neighboring magnetic ions.

[0043] In some embodiments, the Heusler alloy is a material selected from a group consisting of: Cu_2MnAl, Cu_2MnIn, Cu_2MnSn, Ni_2MnAl, Ni_2MnIn, Ni_2MnSn, Ni_2MnSb, Ni_2MnGa Co_2MnAl, Co_2MnSi, Co_2MnGa, Co_2MnGe, Pd_2MnAl, Pd_2MnIn, Pd_2MnSn, Pd_2MnSb, Co_2FeSi, Co_2FeAl, Fe_2VAl, Mn_2VGa, Co_2FeGe, MnGa, and MnGaRu.

[0044] In some embodiments, first and second magnetic electrodes (or contacts) 403 and 404 are in-plane magnets. For example, the directions of magnetization of the first and second magnetic electrodes 403 and 404, respectively, are along the length of waveguide 201. In some embodiments, first and second magnetic electrodes (or contacts) 403 and 404 are perpendicular magnets (e.g., with perpendicular magnetic anisotropy). For example, the directions of magnetization of the first and second magnetic electrodes 403 and 404, respectively, are perpendicular to the length of waveguide 201.

[0045] The thickness of first and second magnetic electrodes (or contacts) 403 and 404 may determine their magnetization directions. For example, when the thickness of the ferromagnetic layer is above a certain threshold (depending on the material of the magnet, e.g. approximately 1.5 nm for CoFe), then the ferromagnetic layer exhibits magnetization direction which is in-plane. Likewise, when the thickness of the ferromagnetic layer is below a certain threshold (depending on the material of the magnet), then the ferromagnetic layer exhibits magnetization direction which is perpendicular to the plane of the magnetic layer.

[0046] Other factors may also determine the direction of magnetization. For example, factors such as surface anisotropy (depending on the adjacent layers or a multi-layer composition of the ferromagnetic layer) and/or crystalline anisotropy (depending on stress and the crystal lattice structure modification such as FCC (face centered cubic lattice), BCC (body centered cubic lattice), or L10-type of crystals, where L10 is a type of crystal class which exhibits perpendicular magnetizations), can also determine the direction of magnetization.

[0047] In some embodiments, first and second magnetic electrodes (or contacts) 403 and 404) are formed of a stack of materials, where the materials for the stack are selected from a group consisting of: Co and Pt; Co and Pd; Co and Ni; MgO, CoFeB, Ta, CoFeB, and

MgO; MgO, CoFeB, W, CoFeB, and MgO; MgO, CoFeB, V, CoFeB, and MgO; MgO, CoFeB, Mo, CoFeB, and MgO; Mn_xGa_y; Materials with L10 symmetry; and materials with tetragonal crystal structure. In some embodiments, first and second magnetic electrodes (or contacts) 403 and 404 are formed of a single layer of one or more materials. In some embodiments, the single layer is formed of MnGa. In some embodiments, first and second magnetic electrodes (or contacts) 403 and 404 are formed with interfacial PMA (perpendicular magnetic anisotropy), multi-interface PMA, magnetic crystalline anisotropy or multi-layer PMA.

[0048] **Fig. 5** illustrates mode selected spin orbit material integrated optical device 500 with cavity and with ferromagnet contacts, according to some embodiments of the disclosure. It is pointed out that those elements of **Fig. 5** having the same reference numbers (or names) as the elements of any other figure can operate or function in any manner similar to that described, but are not limited to such. So as not to obscure the embodiment of **Fig. 5**, differences between **Fig. 5** and **Fig. 4** are described.

[0049] In some embodiments, a circular polarizer (or filter) 501 is sandwiched between the layers (e.g., 304a/b and 305a/b) of the Bragg reflector and waveguide 201. In some embodiments, circular polarizer 501 behaves as a mode selector. In some embodiments, circular polarizer 501 is a right circular polarizer. For example, circular polarizer 501 may filter or pass clockwise circularly polarized light. In some embodiments, circular polarizer 501 is a left circular polarizer. For example, circular polarizer 501 may filter or pass counter-clockwise circularly polarized light. In some embodiments, circular polarizer can be rotated along their axis. Any known mechanism can be used for rotating the circular polarizer. Circular polarizer 501 can be used to adjust light reflections as light is provided from waveguide section 305. As such, different absorption for right and left circular polarization is achieved.

[0050] Circular polarizer 501 can also be used for managing input or injected light, which is then converted to spin polarized electrons in magnets 403 and 404. As such, spin up or spin down polarization is achieved by circularly polarizing (right or left) the input injected light. For example, when a right polarized circular polarizer is used, spin up electrons are generated, and when a left polarized circular polarizer is used, spin down electrons are generated, or vice versa. In some embodiments, mode selection spin orbit material laser device 500 produces on/off key optical modulation since left or right circular polarization is not amenable to lasing (e.g., high loss for one of the polarization modes). A person skilled in the art would appreciate that circular polarizers are used for managing light reflections.

[0051] **Fig. 6** illustrates top view 600 of a photonic crystal cavity spin orbit material laser, according to some embodiments of the disclosure. It is pointed out that those elements of **Fig. 6** having the same reference numbers (or names) as the elements of any other figure can operate or function in any manner similar to that described, but are not limited to such.

[0052] In some embodiments, waveguide 601 is a one dimensional (1D) photonic crystal cavity with one or more holes 602. In some embodiments, holes 602 are etched from the host layer 601 and contain vacuum or air. In some embodiments, holes 602 are filled with a transparent dielectric material by the process of deposition. The cavity provides high selectivity to generate light due to optical resonance of the cavity. In some embodiments, the one or more holes 602 are periodic holes formed in waveguide 601. In some embodiments, waveguide 601 is formed of a material selected from a group consisting of: Si, Ge, SiGe, doped SiO_2 glass, SiN, PMMA, polystyrene, diamond, and elements from the group III through V of the periodic table. In some embodiments, the input spin current is injected via magnetic contacts 403 and 404, and the output light propagates out of the optical cavity formed by holes 602. In some embodiments, input light is incident from the outside of the optical cavity formed by holes 602, and the output spin current is received by magnetic contacts 403 and 404.

[0053] **Fig. 7** illustrates plot 700 showing reflectivity of parts of the optical cavity ('mirrors') formed by holes 602 and the overall optical transmittivity of the optical cavity over wavelengths for spin to optical conversion, according to some embodiments of the disclosure. It is pointed out that those elements of **Fig. 7** having the same reference numbers (or names) as the elements of any other figure can operate or function in any manner similar to that described, but are not limited to such. Here, x-axis is wavelength in nanometer, and y-axis is dimensionless optical transmittivity or reflectivity. Plot 700 shows that light is resonant with the cavity at a particular wavelength (e.g., 1550 nm). Therefore, laser emission for spin-to-optical conversion and detection of polarized light for optical-to-spin conversion may occur predominantly at this wavelength.

[0054] **Fig. 8** illustrates top view 800 of an enhanced quality factor two-dimensional photonic crystal cavity spin orbit material laser, according to some embodiments of the disclosure. It is pointed out that those elements of **Fig. 8** having the same reference numbers (or names) as the elements of any other figure can operate or function in any manner similar to that described, but are not limited to such.

[0055] In some embodiments, waveguide 801 is two dimensional (2D) photonic crystal cavity with one or more holes 802. The cavity provides high selectivity to generated light due to optical resonance of the cavity. In some embodiments, the one or more holes 802 are periodic holes formed in waveguide 801. In some embodiments, waveguide 801 is formed of a material selected from a group consisting of: Si, Ge, SiGe, doped SiO_2 glass, SiN, PMMA, polystyrene, diamond, and elements from the group III through V of the periodic table.

[0056] In some embodiments, the input spin current is injected via magnetic contacts 403 and 404, and the output light propagates out of the optical cavity formed by holes 802. In some embodiments, input light is incident from the outside of the optical cavity formed by holes 802, and the output spin current is received by magnetic contacts 403 and 404.

[0057] **Fig. 9** illustrates method flowchart 900 of converting spin electrical signal into optical signal, according to some embodiments of the disclosure. It is pointed out that those elements of **Fig. 9** having the same reference numbers (or names) as the elements of any other figure can operate or function in any manner similar to that described, but are not limited to such. The illustrated embodiments can be performed in a different order, and some actions/blocks may be performed in parallel. Some of the blocks and/or operations listed in **Fig. 9** are optional in accordance with certain embodiments. The numbering of the blocks presented is for the sake of clarity and is not intended to prescribe an order of operations in which the various blocks must occur. Additionally, operations from the various flows may be utilized in a variety of combinations.

[0058] At block 901, a voltage is applied across first and second electrodes (203 and 204). As such, spin polarized electrons are generated in the layer of spin orbit material. The spin polarized electrons annihilate with holes to generate polarized photons. At block 902, the polarized photons are received from one end of the waveguide 201. At block 903, one or more polarizers 501 are adjusted (e.g., clockwise or anti-clock wise) to adjust the polarization of light (i.e., photons).

[0059] **Fig. 10** illustrates method flowchart 1000 of converting optical signal to spin electrical signal, according to some embodiments of the disclosure. It is pointed out that those elements of **Fig. 10** having the same reference numbers (or names) as the elements of any other figure can operate or function in any manner similar to that described, but are not limited to such. The illustrated embodiments can be performed in a different order, and some actions/blocks may be performed in parallel. Some of the blocks and/or operations listed in **Fig. 10** are optional in accordance with certain embodiments. The numbering of the blocks presented is for the sake of clarity and is not intended to prescribe an order of operations in which the various blocks must occur. Additionally, operations from the various flows may be utilized in a variety of combinations.

[0060] At block 1001, light is injected into waveguide 201. For example, a light source (e.g., a spin-to-light transducer) provides photons to one end of waveguide 201. The injected light causes electrons in the spin orbit material layer (202 or 302) to become spin polarized. These spin polarized electrons that then detected by electrodes 203 and 204 (e.g., via a voltage detector) or by ferromagnets 403 and 404. At block 1002, current flow is detected from first electrode 203 to second electrode 204. At block 1003, one or more polarizers 501 are adjusted (e.g., clockwise or anti-clock wise) to adjust the polarization of injected photons. As such, spin-up or spin-down electrons are achieved in ferromagnets 403 and 404. For example, if one or more polarizers 501 convert the light polarization from vertical linear to right circular, spin up electrons are detected in ferromagnets 403 and 404. In another example, if one or more polarizers 501 convert the light polarization from vertical linear to left circular, spin down electrons are detected in ferromagnets 403 and 404.

[0061] **Fig. 11** illustrates a smart device or a computer system or a SoC (System-on-Chip) with a spin-optical transducer (e.g., 101 and/or 102), according to some embodiments of the disclosure. It is pointed out that those elements of **Fig. 11** having the same reference numbers (or names) as the elements of any other figure can operate or function in any manner similar to that described, but are not limited to such.

[0062] For purposes of the embodiments, the transistors in various circuits and logic blocks described here are metal oxide semiconductor (MOS) transistors or their derivatives, where the MOS transistors include drain, source, gate, and bulk terminals. The transistors and/or the MOS transistor derivatives also include Tri-Gate and FinFET transistors, Gate All Around Cylindrical Transistors, Tunneling FET (TFET), Square Wire, or Rectangular Ribbon Transistors, ferroelectric FET (FeFETs), or other devices implementing transistor functionality like carbon nanotubes or spintronic devices. MOSFET symmetrical source and drain terminals i.e., are identical terminals and are interchangeably used here. A TFET device, on the other hand, has asymmetric Source and Drain terminals. Those skilled in the art will appreciate that other transistors, for example, Bi-polar junction transistors (BJT PNP/NPN), BiCMOS, CMOS, etc., may be used without departing from the scope of the disclosure.

[0063] In some embodiments, computing device 1600 represents a mobile computing device, such as a computing tablet, a mobile phone or smart-phone, a wireless-enabled e-reader, or other wireless mobile device. It will be understood that certain components are shown generally, and not all components of such a device are shown in computing device 1600.

[0064] In some embodiments, optical-to-spin converter 101 and/or spin-to-topical converter 102 is provided in computing device 1600. In some embodiments, computing device 1600 includes first processor 1610 with spin-optical transducer, according to some embodiments discussed. Other blocks of the computing device 1600 may also include spin-optical transducer, according to some embodiments. The various embodiments of the present disclosure may also comprise a network interface within 1670 such as a wireless interface so that a system embodiment may be incorporated into a wireless device, for example, cell phone or personal digital assistant.

[0065] In some embodiments, processor 1610 (and/or processor 1690) can include one or more physical devices, such as microprocessors, application processors, microcontrollers, programmable logic devices, or other processing means. The processing operations performed by processor 1610 include the execution of an operating platform or operating system on which applications and/or device functions are executed. The processing operations include operations related to I/O (input/output) with a human user or with other devices, operations related to power management, and/or operations related to connecting the computing device 1600 to another device. The processing operations may also include operations related to audio I/O and/or display I/O.

[0066] In some embodiments, computing device 1600 includes audio subsystem 1620, which represents hardware (e.g., audio hardware and audio circuits) and software (e.g., drivers, codecs) components associated with providing audio functions to the computing device. Audio functions can include speaker and/or headphone output, as well as microphone input. Devices for such functions can be integrated into computing device 1600, or connected to the computing device 1600. In one embodiment, a user interacts with the computing device 1600 by providing audio commands that are received and processed by processor 1610.

[0067] In some embodiments, computing device 1600 comprises display subsystem 1630. Display subsystem 1630 represents hardware (e.g., display devices) and software (e.g., drivers) components that provide a visual and/or tactile display for a user to interact with the computing device 1600. Display subsystem 1630 includes display interface 1632, which includes the particular screen or hardware device used to provide a display to a user. In one embodiment, display interface 1632 includes logic separate from processor 1610 to perform at least some processing related to the display. In one embodiment, display subsystem 1630 includes a touch screen (or touch pad) device that provides both output and input to a user.

[0068] In some embodiments, computing device 1600 comprises I/O controller 1640. I/O controller 1640 represents hardware devices and software components related to interaction with a user. I/O controller 1640 is operable to manage hardware that is part of audio subsystem 1620 and/or display subsystem 1630. Additionally, I/O controller 1640 illustrates a connection point for additional devices that connect to computing device 1600 through which a user might interact with the system. For example, devices that can be attached to the computing device 1600 might include microphone devices, speaker or stereo systems, video systems or other display devices, keyboard or keypad devices, or other I/O devices for use with specific applications such as card readers or other devices.

[0069] As mentioned above, I/O controller 1640 can interact with audio subsystem 1620 and/or display subsystem 1630. For example, input through a microphone or other audio device can provide input or commands for one or more applications or functions of the computing device 1600. Additionally, audio output can be provided instead of, or in addition to display output. In another example, if display subsystem 1630 includes a touch screen, the display device also acts as an input device, which can be at least partially managed by I/O controller 1640. There can also be additional buttons or switches on the computing device 1600 to provide I/O functions managed by I/O controller 1640.

[0070] In some embodiments, I/O controller 1640 manages devices such as accelerometers, cameras, light sensors or other environmental sensors, or other hardware that can be included in the computing device 1600. The input can be part of direct user interaction, as well as providing environmental input to the system to influence its operations (such as filtering for noise, adjusting displays for brightness detection, applying a flash for a camera, or other features).

[0071] In some embodiments, computing device 1600 includes power management 1650 that manages battery power usage, charging of the battery, and features related to power saving operation. Memory subsystem 1660 includes memory devices for storing information in computing device 1600. Memory can include nonvolatile (state does not change if power to the memory device is interrupted) and/or volatile (state is indeterminate if power to the memory device is interrupted) memory devices. Memory subsystem 1660 can store application data, user data, music, photos, documents, or other data, as well as system data (whether long-term or temporary) related to the execution of the applications and functions of the computing device 1600.

[0072] Elements of embodiments are also provided as a machine-readable medium (e.g., memory 1660) for storing the computer-executable instructions (e.g., instructions to implement any other processes discussed herein). The machine-readable medium (e.g., memory 1660) may include, but is not limited to, flash memory, optical disks, CD-ROMs, DVD ROMs, RAMs, EPROMs, EEPROMs, magnetic or optical cards, phase change memory (PCM), or other types of machine-readable media suitable for storing electronic or computer-executable instructions. For example, embodiments of the disclosure may be downloaded as a computer program (e.g., BIOS) which may be transferred from a remote computer (e.g., a server) to a requesting computer (e.g., a client) by way of data signals via a communication link (e.g., a modem or network connection).

[0073] In some embodiments, computing device 1600 comprises connectivity 1670. Connectivity 1670 includes hardware devices (e.g., wireless and/or wired connectors and communication hardware) and software components (e.g., drivers, protocol stacks) to enable the computing device 1600 to communicate with external devices. The computing device 1600 could be separate devices, such as other computing devices, wireless access points or base stations, as well as peripherals such as headsets, printers, or other devices.

[0074] Connectivity 1670 can include multiple different types of connectivity. To generalize, the computing device 1600 is illustrated with cellular connectivity 1672 and wireless connectivity 1674. Cellular connectivity 1672 refers generally to cellular network connectivity provided by wireless carriers, such as provided via GSM (global system for mobile communications) or variations or derivatives, CDMA (code division multiple access) or variations or derivatives, TDM (time division multiplexing) or variations or derivatives, or other cellular service standards. Wireless connectivity (or wireless interface) 1674 refers to wireless connectivity that is not cellular, and can include personal area networks (such as Bluetooth, Near Field, etc.), local area networks (such as Wi-Fi), and/or wide area networks (such as WiMax), or other wireless communication. In some embodiments, Connectivity 1670 includes parallel sensing arrays as described with reference to **Figs. 10-13**.

[0075] In some embodiments, computing device 1600 comprises peripheral connections 1680. Peripheral connections 1680 include hardware interfaces and connectors, as well as software components (e.g., drivers, protocol stacks) to make peripheral connections. It will be understood that the computing device 1600 could both be a peripheral device ("to" 1682) to other computing devices, as well as have peripheral devices ("from" 1684) connected to it. The computing device 1600 commonly has a "docking" connector to connect to other computing devices for purposes such as managing (e.g., downloading and/or uploading, changing, synchronizing) content on computing device 1600. Additionally, a docking connector can allow computing device 1600 to connect to certain peripherals that allow the computing device 1600 to control content output, for example, to audiovisual or other systems.

[0076] In addition to a proprietary docking connector or other proprietary connection hardware, the computing device 1600 can make peripheral connections 1680 via common or standards-based connectors. Common types can include a Universal Serial Bus (USB) connector (which can include any of a number of different hardware interfaces), DisplayPort including MiniDisplayPort (MDP), High Definition Multimedia Interface (HDMI), Firewire, or other types.

[0077] Reference in the specification to "an embodiment," "one embodiment," "some embodiments," or "other embodiments" means that a particular feature, structure, or characteristic described in connection with the embodiments is included in at least some embodiments, but not necessarily all embodiments. The various appearances of "an embodiment," "one embodiment," or "some embodiments" are not necessarily all referring to the same embodiments. If the specification states a component, feature, structure, or characteristic "may," "might," or "could" be included, that particular component, feature, structure, or characteristic is not required to be included. If the specification or claim refers to "a" or "an" element, that does not mean there is only one of the elements. If the specification or claims refer to "an additional" element, that does not preclude there being more than one of the additional element.

[0078] Furthermore, the particular features, structures, functions, or characteristics may be combined in any suitable manner in one or more embodiments. For example, a first embodiment may be combined with a second embodiment anywhere the particular features, structures, functions, or characteristics associated with the two embodiments are not mutually exclusive.

[0079] While the disclosure has been described in conjunction with specific embodiments thereof, many alternatives, modifications and variations of such embodiments will be apparent to those of ordinary skill in the art in light of the foregoing description. The embodiments of the disclosure are intended to embrace all such alternatives, modifications, and variations as to fall within the broad scope of the appended claims.

[0080] In addition, well known power/ground connections to integrated circuit (IC) chips and other components may or may not be shown within the presented figures, for simplicity of illustration and discussion, and so as not to obscure the disclosure. Further, arrangements may be shown in block diagram form in order to avoid obscuring the disclosure, and also in view of the fact that specifics with respect to implementation of such block diagram arrangements are highly dependent upon the platform within which the present disclosure is to be implemented (i.e., such specifics should be well within purview of one skilled in the art). Where specific details (e.g., circuits) are set forth in order to describe example embodiments of the disclosure, it should be apparent to one skilled in the art that the disclosure can be practiced without, or with variation of, these specific details. The description is thus to be regarded as illustrative instead of limiting.

[0081] The following examples pertain to further embodiments. Specifics in the examples may be used anywhere in one or more embodiments. All optional features of the apparatus described herein may also be implemented with respect to a method or process.

[0082] For example, an apparatus is provided which comprises: a waveguide; and a layer of material with high spin orbit coupling material adjacent to the waveguide. In some embodiments, the apparatus comprises a first electrode doped with n-type dopant, wherein the first electrode is adjacent to the layer of high spin orbit coupling material. In some embodiments, the apparatus comprises a second electrode doped with a p-type dopant, wherein the second electrode is adjacent to the layer of high spin orbit coupling material, and wherein the first and second electrodes are separated from one another. In some embodiments, the first and second electrodes comprises a material selected from a group consisting of: Cu, Ag, Au, and Al. In some embodiments, the apparatus comprises a first set of Bragg reflectors adjacent to a first end of the waveguide. In some embodiments, the apparatus comprises a circular polarizer sandwiched between the first set of Bragg reflectors and the first end of the waveguide. In some embodiments, the apparatus comprises a second set of Bragg reflectors adjacent to another end of the waveguide. In some embodiments, the layer of high spin orbit coupling material comprises a material selected from a group consisting of: graphene, TiS_2, WS_2, MoS_2, $TiSe_2$, WSe_2, $MoSe_2$, B_2S_3, Sb_2S_3, Ta_2S, Re_2S_7, $LaCPS_2$, $LaOAsS_2$, $ScOBiS_2$, $GaOBiS_2$, $AlOBiS_2$, $LaOSbS_2$, $BiOBiS_2$, $YOBiS_2$, $InOBiS_2$, $LaOBiSe_2$, $TiOBiS_2$, $CeOBiS_2$, $PrOBiS_2$, $NdOBiS_2$, $LaOBiS_2$, and $SrFBiS_2$. In some embodiments, the waveguide comprises a material selected from a group consisting of: Si, SiN, Diamond, elements from the group III column of the periodic column through V of the periodic table. In some embodiments, the waveguide comprises micro ring resonators. In some embodiments, the waveguide includes holes.

[0083] In another example, a system is provided which comprises: a memory; a processor coupled to the memory, the processor having an apparatus according to the apparatus described above; and a wireless interface for allowing the processor to communicate with another device.

[0084] In another example, an apparatus is provided which comprises: a waveguide; a layer of high spin orbit coupling material adjacent to the waveguide; a first ferromagnet adjacent to the layer of high spin orbit coupling material; and a second ferromagnet adjacent to the layer of high spin orbit coupling material, wherein the first and second ferromagnets are separated from one another by a distance. In some embodiments, the first and second ferromagnets comprises one or a combination of materials selected from a group consisting of a Heusler alloy, Co, Fe, Ni, Gd, B, Ge, Ga, permalloy, and Yttrium Iron Garnet (YIG). In some embodiments, the Heusler alloy is a material selected from a group consisting of: Cu_2MnAl, Cu_2MnIn, Cu_2MnSn, Ni_2MnAl, Ni_2MnIn, Ni_2MnSn, Ni_2MnSb, Ni_2MnGa Co_2MnAl, Co_2MnSi, Co_2MnGa, Co_2MnGe, Pd_2MnAl, Pd_2MnIn, Pd_2MnSn, Pd_2MnSb, Co_2FeSi, Co_2FeAl, Fe_2VAl, Mn_2VGa, Co_2FeGe, MnGa, and MnGaRu. In some embodiments, the first and second ferromagnets comprises a stack of materials, wherein the materials for the stack are selected from a group consisting of: Co and Pt; Co and Pd; Co and Ni; MgO, CoFeB, Ta, CoFeB, and MgO; MgO, CoFeB, W, CoFeB, and MgO; MgO, CoFeB, V, CoFeB, and MgO; MgO, CoFeB, Mo, CoFeB, and MgO; Mn_xGa_y; Materials with L10 symmetry; and materials with tetragonal crystal structure. In some embodiments, the layer of high spin orbit coupling material comprises a material selected from a group consisting of: graphene, TiS_2, WS_2, MoS_2, $TiSe_2$, WSe_2, $MoSe_2$, B_2S_3, Sb_2S_3, Ta_2S, Re_2S_7, $LaCPS_2$, $LaOAsS_2$, $ScOBiS_2$, $GaOBiS_2$, $AlOBiS_2$, $LaOSbS_2$, $BiOBiS_2$, $YOBiS_2$, $InOBiS_2$, $LaOBiSe_2$, $TiOBiS_2$, $CeOBiS_2$, $PrOBiS_2$, $NdOBiS_2$, $LaOBiS_2$, and $SrFBiS_2$. In some embodiments, the first and second ferromagnets comprises a single layer of one or more materials. In some embodiments, the single layer is formed of MnGa. In some embodiments, the apparatus comprises a first set of Bragg reflectors adjacent to a first end of the waveguide. In some embodiments, the apparatus comprises a circular polarizer sandwiched between the first set of Bragg reflectors and the first end of the waveguide. In some embodiments, the apparatus comprising a second set of Bragg reflectors adjacent to another end of the waveguide. In some embodiments, the waveguide comprises a material selected from a group consisting of: Si, SiN, Diamond, and elements from the group III column of the periodic column through V of the periodic table. In some embodiments, the waveguide comprises micro ring resonators. In some embodiments, the waveguide includes holes.

[0085] In another example, a system is provided which comprises: a memory; a processor coupled to the memory, the processor having an apparatus according to the apparatus described above; and a wireless interface for allowing the processor to communicate with another device.

[0086] In another example, a method is provided which comprises applying a voltage across first and second electrodes, wherein the first and second electrodes are adjacent to a layer of high spin orbit coupling material; and receiving photons from one end of a waveguide which is adjacent to the layer of high spin orbit coupling material. In some embodiments, the method comprises adjusting direction of a polarizer, coupled to the waveguide, to adjust direction of the photons. In some embodiments, the first and second electrodes comprises a material selected from a group consisting of: Cu, Ag, Au, and Al. In some embodiments, the layer of di-chalcogenide comprises a material selected from a group consisting of: graphene, TiS_2, WS_2, MoS_2, $TiSe_2$, WSe_2, $MoSe_2$, B_2S_3, Sb_2S_3, Ta_2S, Re_2S_7, $LaCPS_2$, $LaOAsS_2$, $ScOBiS_2$, $GaOBiS_2$, $AlOBiS_2$, $LaOSbS_2$, $BiOBiS_2$, $YOBiS_2$, $InOBiS_2$, $LaOBiSe_2$, $TiOBiS_2$, $CeOBiS_2$, $PrOBiS_2$, $NdOBiS_2$, $LaOBiS_2$, and $SrFBiS_2$.

[0087] In another example, a method is provided which comprises: injecting light into a waveguide; and detecting a current flow from a first electrode to a second electrode, wherein the first and second electrodes are adjacent to a layer of high spin orbit coupling material. In some embodiments, the method comprises adjusting direction of a polarizer, coupled to the waveguide, to adjust direction of the injected light. In some embodiments, the first and second electrodes comprises a material selected from a group consisting of: Cu, Ag, Au, and Al. In some embodiments, the layer of high spin orbit coupling material comprises a material selected from a group consisting of: graphene, TiS_2, WS_2, MoS_2, $TiSe_2$, WSe_2, $MoSe_2$, B_2S_3, Sb_2S_3, Ta_2S, Re_2S_7, $LaCPS_2$, $LaOAsS_2$, $ScOBiS_2$, $GaOBiS_2$, $AlOBiS_2$, $LaOSbS_2$, $BiOBiS_2$, $YOBiS_2$, $InOBiS_2$, $LaOBiSe_2$, $TiOBiS_2$, $CeOBiS_2$, $PrOBiS_2$, $NdOBiS_2$, $LaOBiS_2$, and $SrFBiS_2$.

[0088] An abstract is provided that will allow the reader to ascertain the nature and gist of the technical disclosure. The abstract is submitted with the understanding that it will not be used to limit the scope or meaning of the claims. The following claims are hereby incorporated into the detailed description, with each claim standing on its own as a separate embodiment.

CLAIMS

We claim:

1. An apparatus comprising:

   a waveguide; and

   a layer of material with high spin orbit coupling material adjacent to the waveguide.

2. The apparatus of claim 1 comprising a first electrode doped with n-type dopant, wherein the first electrode is adjacent to the layer of high spin orbit coupling material.

3. The apparatus of claim 2 comprising a second electrode doped with a p-type dopant, wherein the second electrode is adjacent to the layer of high spin orbit coupling material, and wherein the first and second electrodes are separated from one another.

4. The apparatus of claim 3, wherein the first and second electrodes comprises a material selected from a group consisting of: Cu, Ag, Au, and Al.

5. The apparatus of claim 1 comprising a first set of Bragg reflectors adjacent to a first end of the waveguide.

6. The apparatus of claim 5 comprising a circular polarizer sandwiched between the first set of Bragg reflectors and the first end of the waveguide.

7. The apparatus of claim 5 comprising a second set of Bragg reflectors adjacent to another end of the waveguide.

8. The apparatus of claim 1, wherein the layer of high spin orbit coupling material comprises a material selected from a group consisting of: graphene, TiS_2, WS_2, MoS_2, $TiSe_2$, WSe_2, $MoSe_2$, B_2S_3, Sb_2S_3, Ta_2S, Re_2S_7, $LaCPS_2$, $LaOAsS_2$, $ScOBiS_2$, $GaOBiS_2$, $AlOBiS_2$, $LaOSbS_2$, $BiOBiS_2$, $YOBiS_2$, $InOBiS_2$, $LaOBiSe_2$, $TiOBiS_2$, $CeOBiS_2$, $PrOBiS_2$, $NdOBiS_2$, $LaOBiS_2$, and $SrFBiS_2$.

9. The apparatus of claim 1, wherein the waveguide comprises a material selected from a group consisting of: Si, SiN, Diamond, elements from the group III column of the periodic column through V of the periodic table.

10. The apparatus of claim 1, wherein the waveguide comprises micro ring resonators.

11. The apparatus of claim 1, wherein the waveguide includes holes.

12. An apparatus comprising:

a waveguide;

a layer of high spin orbit coupling material adjacent to the waveguide;

a first ferromagnet adjacent to the layer of high spin orbit coupling material; and

a second ferromagnet adjacent to the layer of high spin orbit coupling material,

wherein the first and second ferromagnets are separated from one another by a distance.

13. The apparatus of claim 12, wherein the first and second ferromagnets comprises one or a combination of materials selected from a group consisting of a Heusler alloy, Co, Fe, Ni, Gd, B, Ge, Ga, permalloy, and Yttrium Iron Garnet (YIG).

14. The apparatus of claim 13, wherein the Heusler alloy is a material selected from a group consisting of: Cu_2MnAl, Cu_2MnIn, Cu_2MnSn, Ni_2MnAl, Ni_2MnIn, Ni_2MnSn, Ni_2MnSb, Ni_2MnGa Co_2MnAl, Co_2MnSi, Co_2MnGa, Co_2MnGe, Pd_2MnAl, Pd_2MnIn, Pd_2MnSn, Pd_2MnSb, Co_2FeSi, Co_2FeAl, Fe_2VAl, Mn_2VGa, Co_2FeGe, MnGa, and MnGaRu.

15. The apparatus of claim 12, wherein the first and second ferromagnets comprises a stack of materials, wherein the materials for the stack are selected from a group consisting of: Co and Pt; Co and Pd; Co and Ni; MgO, CoFeB, Ta, CoFeB, and MgO; MgO, CoFeB, W, CoFeB, and MgO; MgO, CoFeB, V, CoFeB, and MgO; MgO, CoFeB, Mo, CoFeB, and MgO; Mn_xGa_y; Materials with L10 symmetry; and materials with tetragonal crystal structure.

16. The apparatus of claim 12, wherein the layer of high spin orbit coupling material comprises a material selected from a group consisting of: graphene, TiS_2, WS_2, MoS_2, $TiSe_2$, WSe_2, $MoSe_2$, B_2S_3, Sb_2S_3, Ta_2S, Re_2S_7, $LaCPS_2$, $LaOAsS_2$, $ScOBiS_2$, $GaOBiS_2$, $AlOBiS_2$, $LaOSbS_2$, $BiOBiS_2$, $YOBiS_2$, $InOBiS_2$, $LaOBiSe_2$, $TiOBiS_2$, $CeOBiS_2$, $PrOBiS_2$, $NdOBiS_2$, $LaOBiS_2$, and $SrFBiS_2$.

17. The apparatus of claim 12, wherein the first and second ferromagnets comprises a single layer of one or more materials.

18. The apparatus of claim 17, wherein the single layer is formed of MnGa.

19. The apparatus of claim 12 comprising a first set of Bragg reflectors adjacent to a first end of the waveguide.

20. The apparatus of claim 19 comprising a circular polarizer sandwiched between the first set of Bragg reflectors and the first end of the waveguide.

21. The apparatus of claim 19 comprising a second set of Bragg reflectors adjacent to another end of the waveguide.

22. The apparatus of claim 12, wherein the waveguide comprises a material selected from a group consisting of: Si, SiN, Diamond, and elements from the group III column of the periodic column through V of the periodic table.

23. The apparatus of claim 12, wherein the waveguide comprises micro ring resonators.

24. The apparatus of claim 12, wherein the waveguide includes holes.

25. A system comprising:

a memory;

a processor coupled to the memory, the processor having an apparatus according to any one of apparatus claims 1 to 11; and

a wireless interface for allowing the processor to communicate with another device.

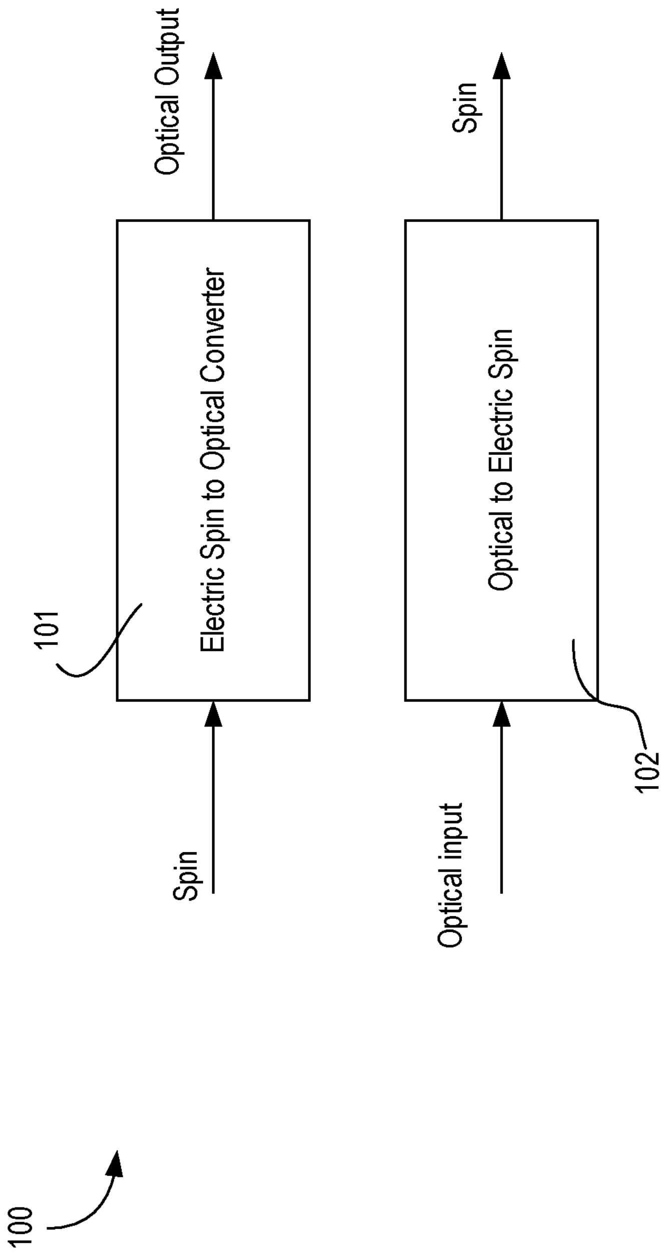
Optical Output
Spin
Electric Spin to Optical Converter
Optical to Electric Spin
101
Spin
Optical input
102
100

Fig. 1

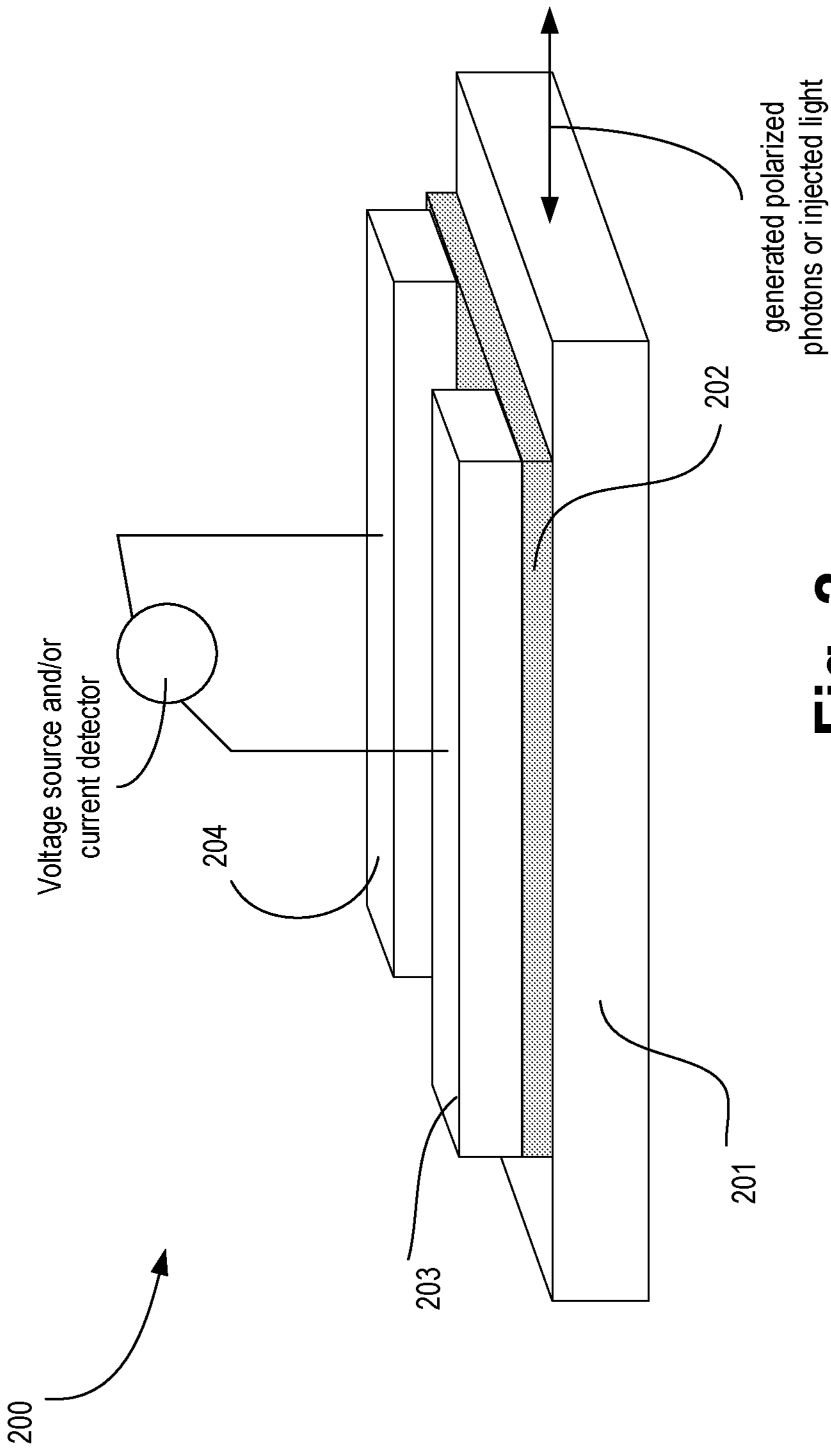
generated polarized photons or injected light
202
Voltage source and/or current detector
204
203
201
200

Fig. 2

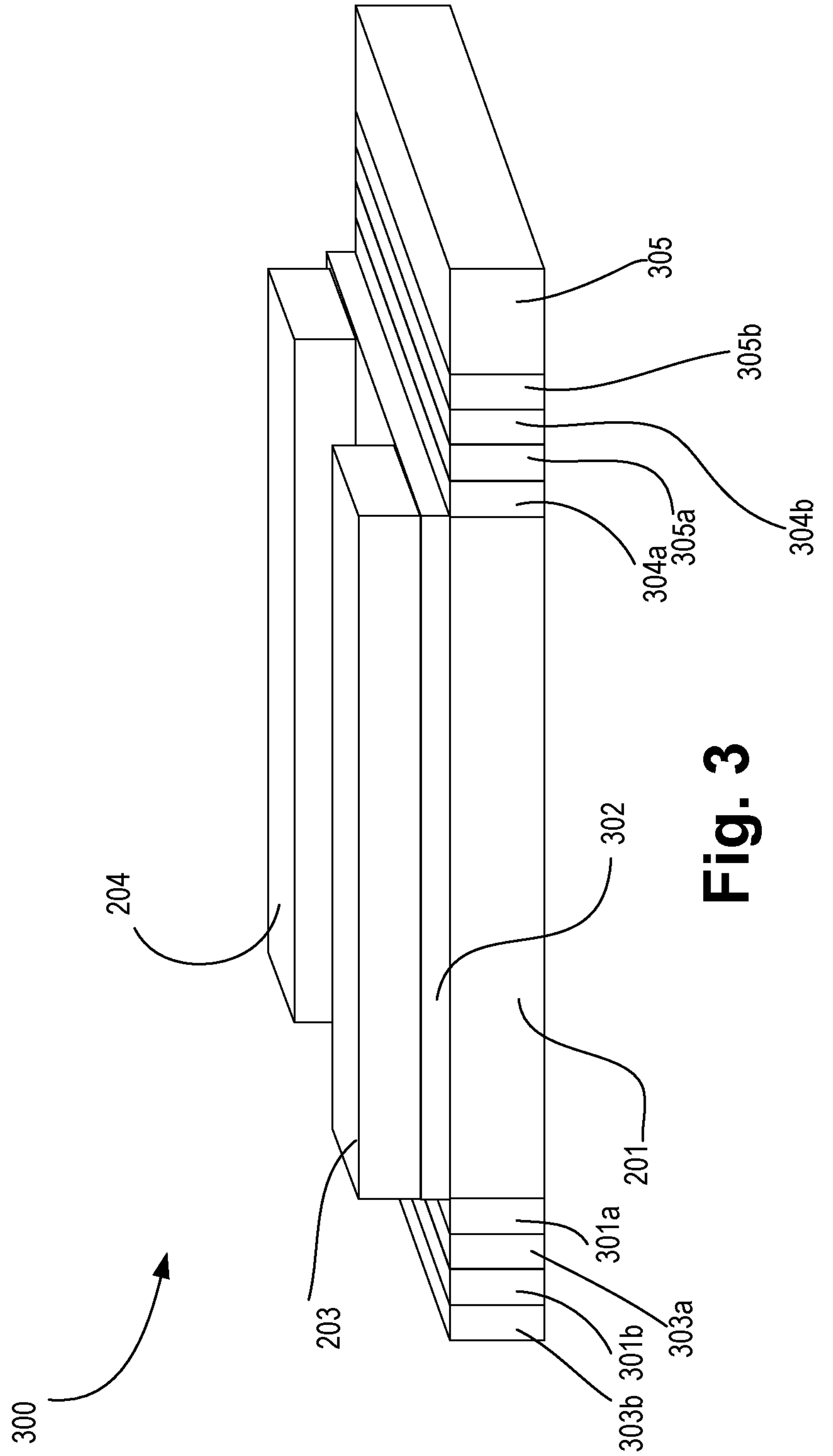
305
305b
304b
305a
304a
204
302
201
203
301a
303a
301b
303b
300

Fig. 3

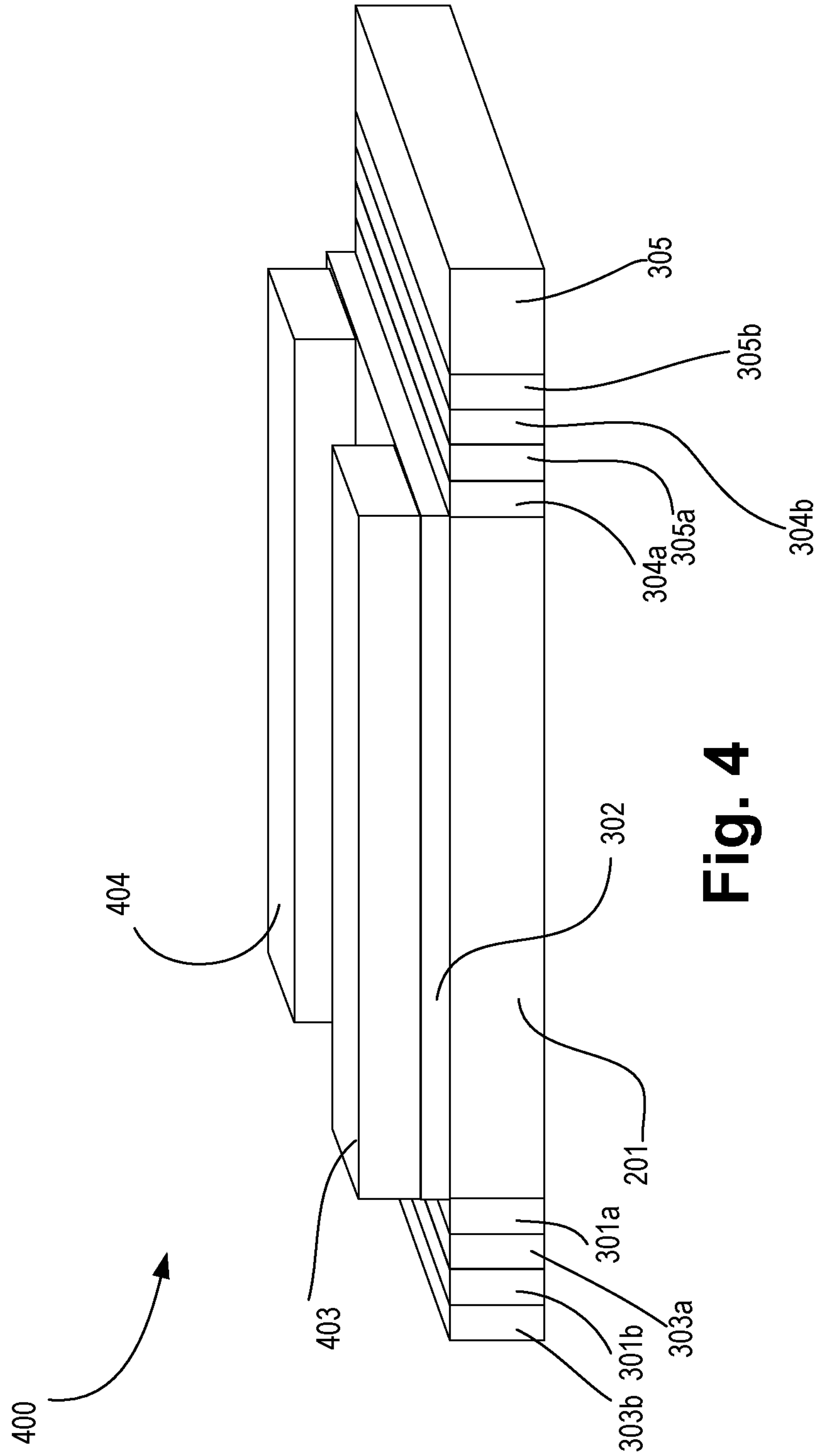
305
305b
304b
305a
304a
404
302
201
403
301a
303a
301b
303b
400

Fig. 4

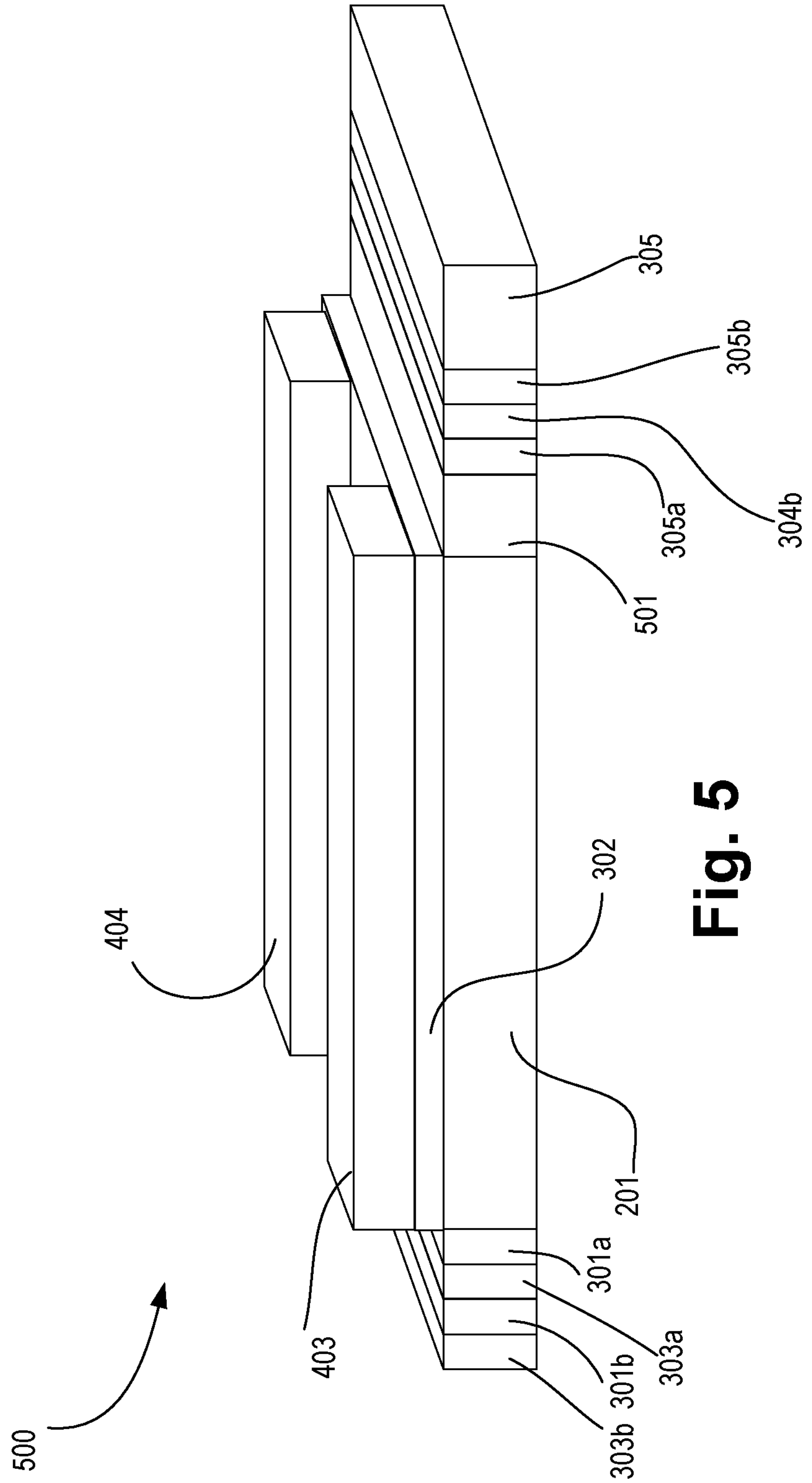

Fig. 5

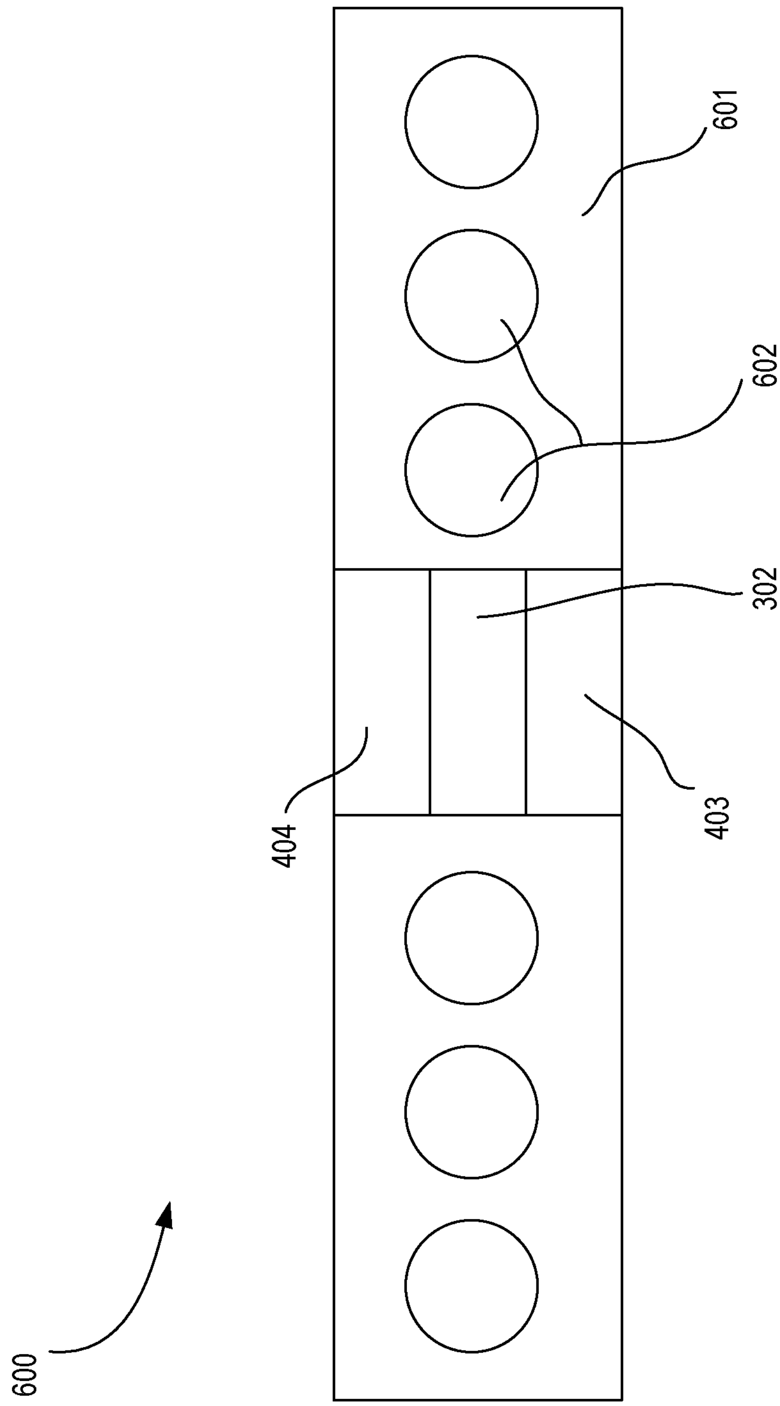

Fig. 6

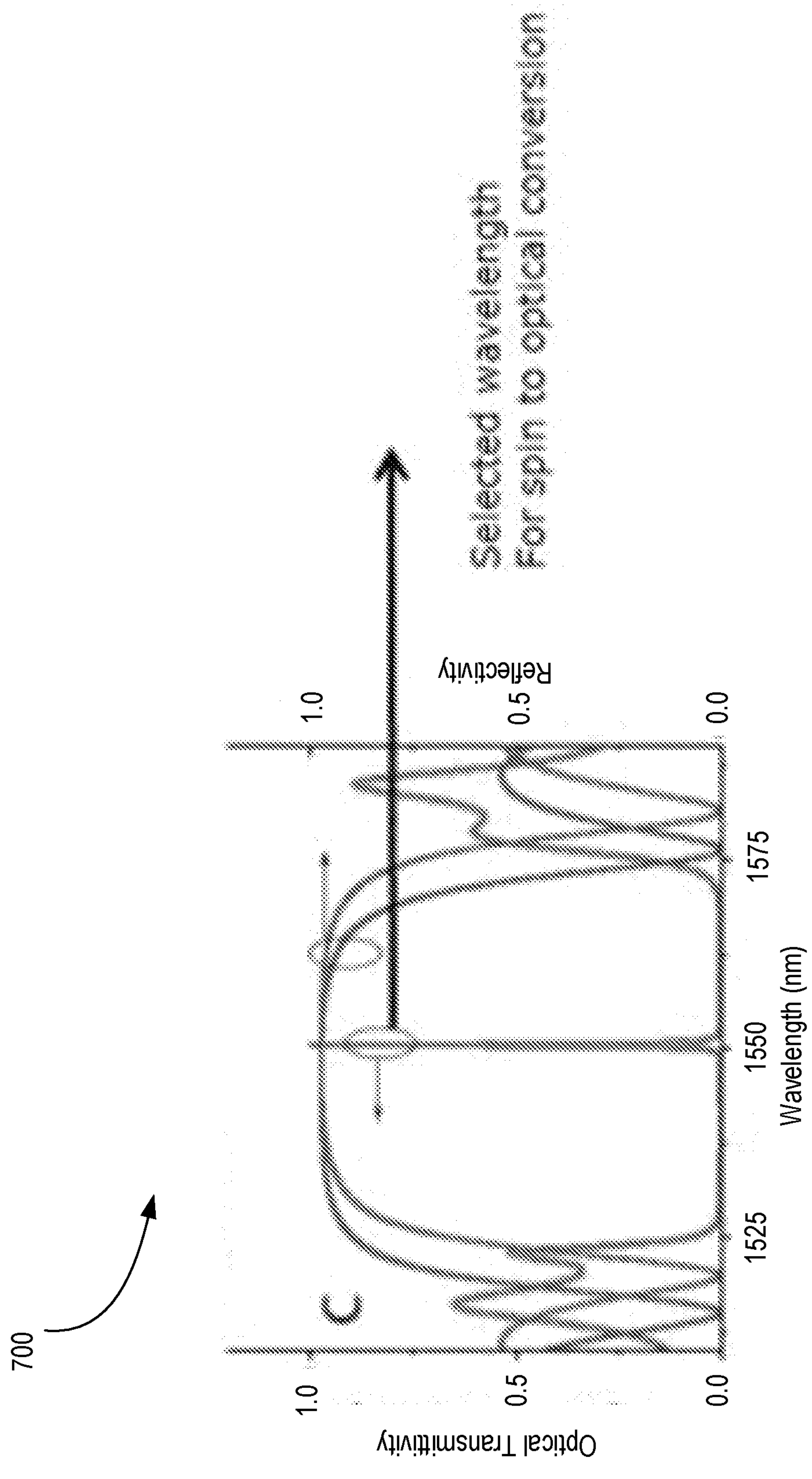
700
C
Optical Transmittivity
1.0
0.5
0.0
Wavelength (nm)
1525
1550
1575
Reflectivity
Selected wavelength
For spin to optical conversion

Fig. 7

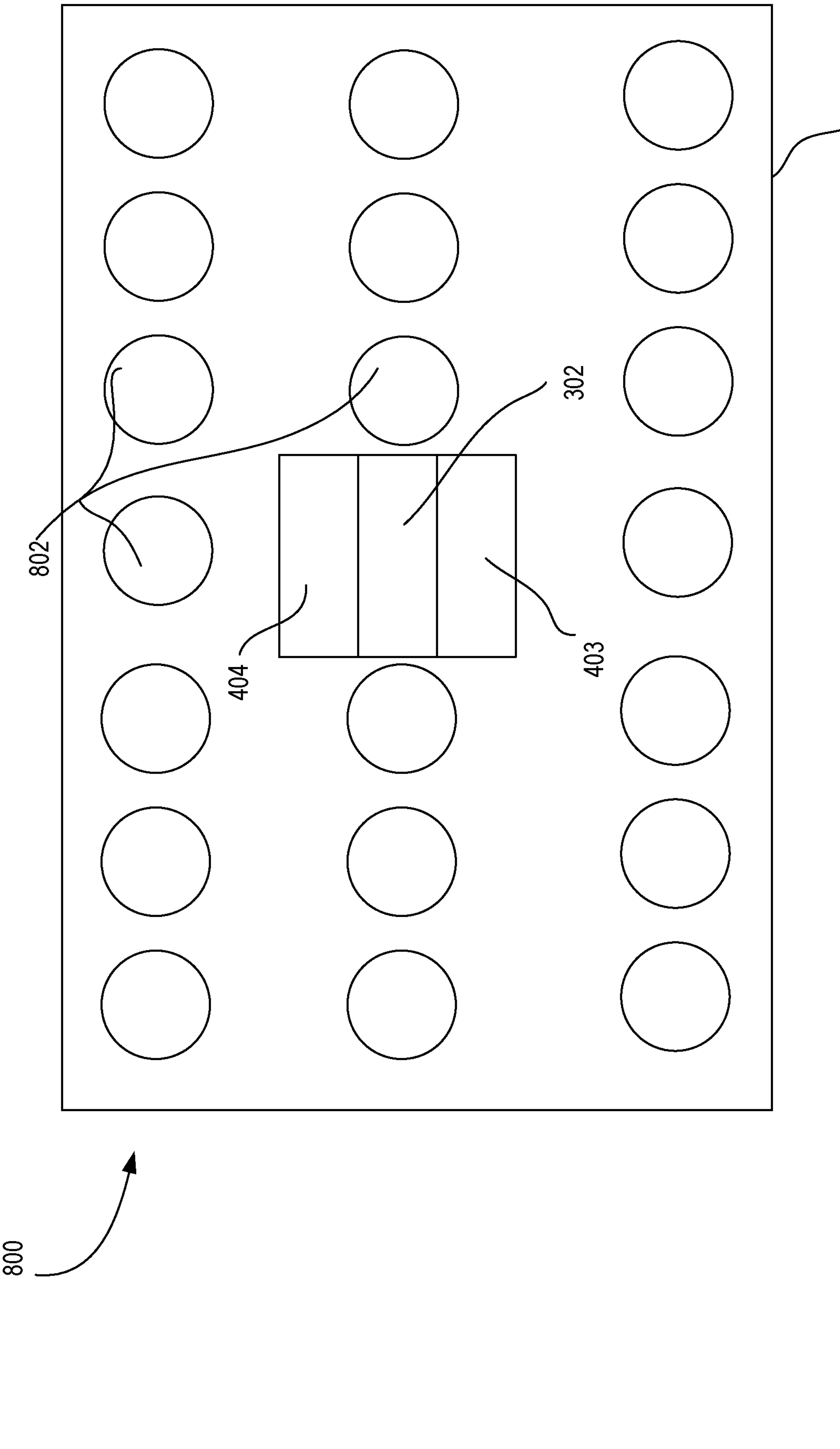

Fig. 8

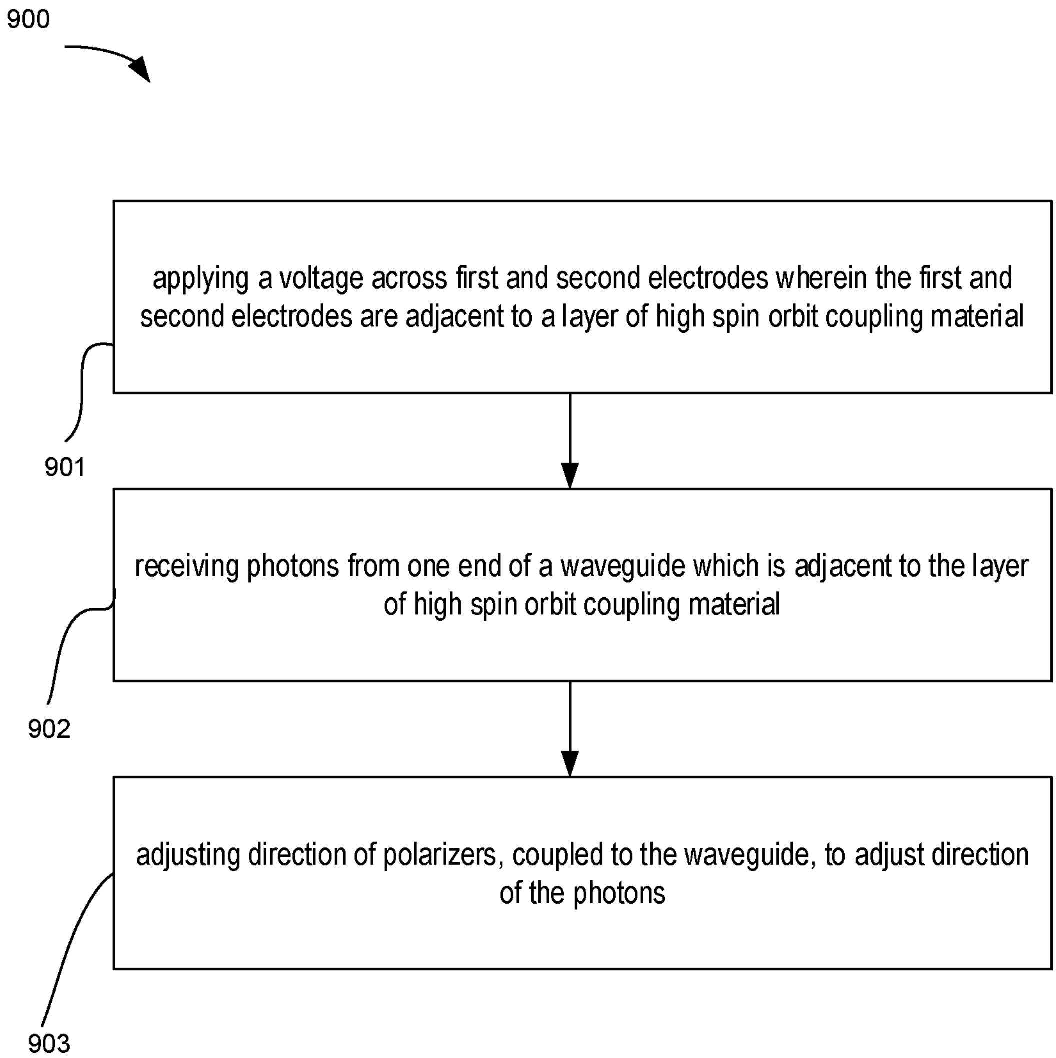
900
applying a voltage across first and second electrodes wherein the first and second electrodes are adjacent to a layer of high spin orbit coupling material
901
receiving photons from one end of a waveguide which is adjacent to the layer of high spin orbit coupling material
902
adjusting direction of polarizers, coupled to the waveguide, to adjust direction of the photons
903

Fig. 9

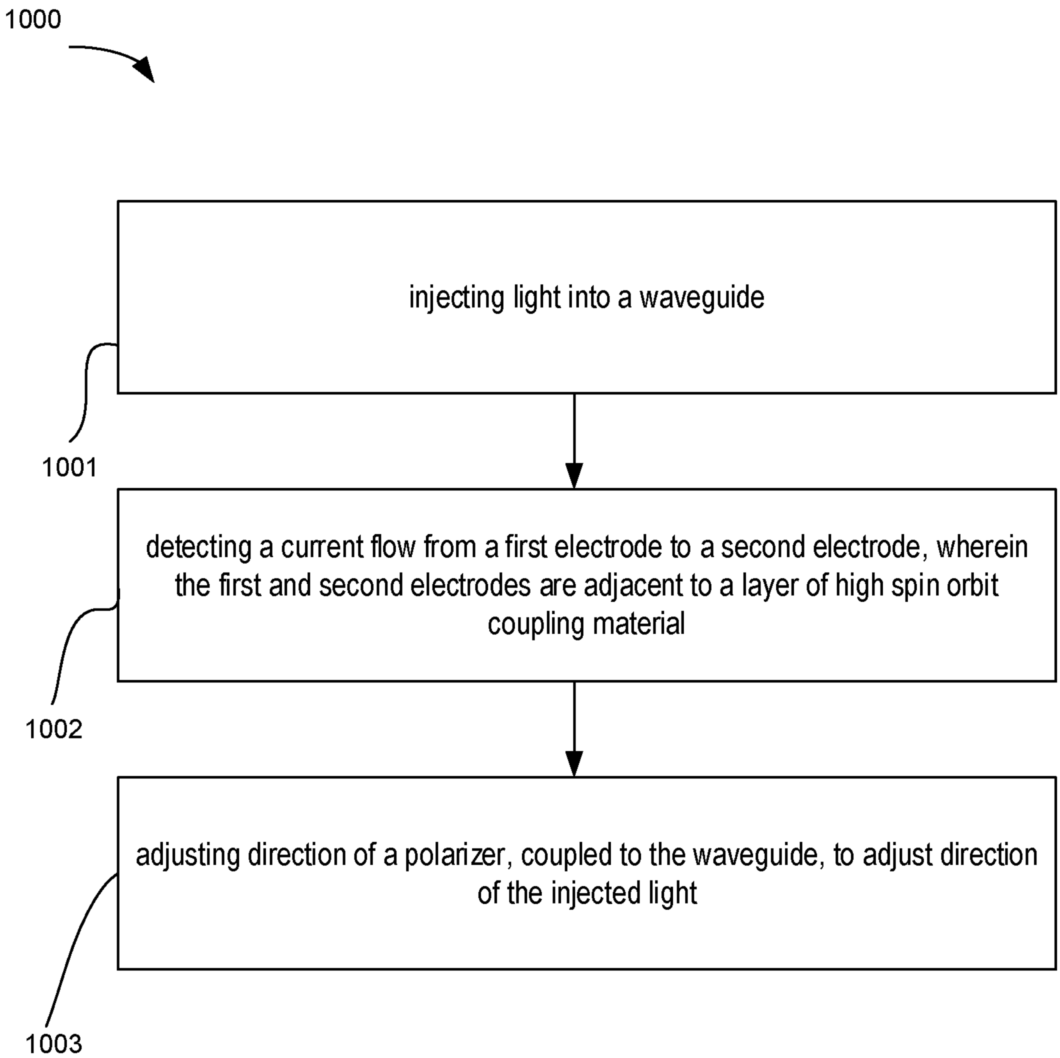
1000
injecting light into a waveguide
1001
detecting a current flow from a first electrode to a second electrode, wherein the first and second electrodes are adjacent to a layer of high spin orbit coupling material
1002
adjusting direction of a polarizer, coupled to the waveguide, to adjust direction of the injected light
1003

Fig. 10

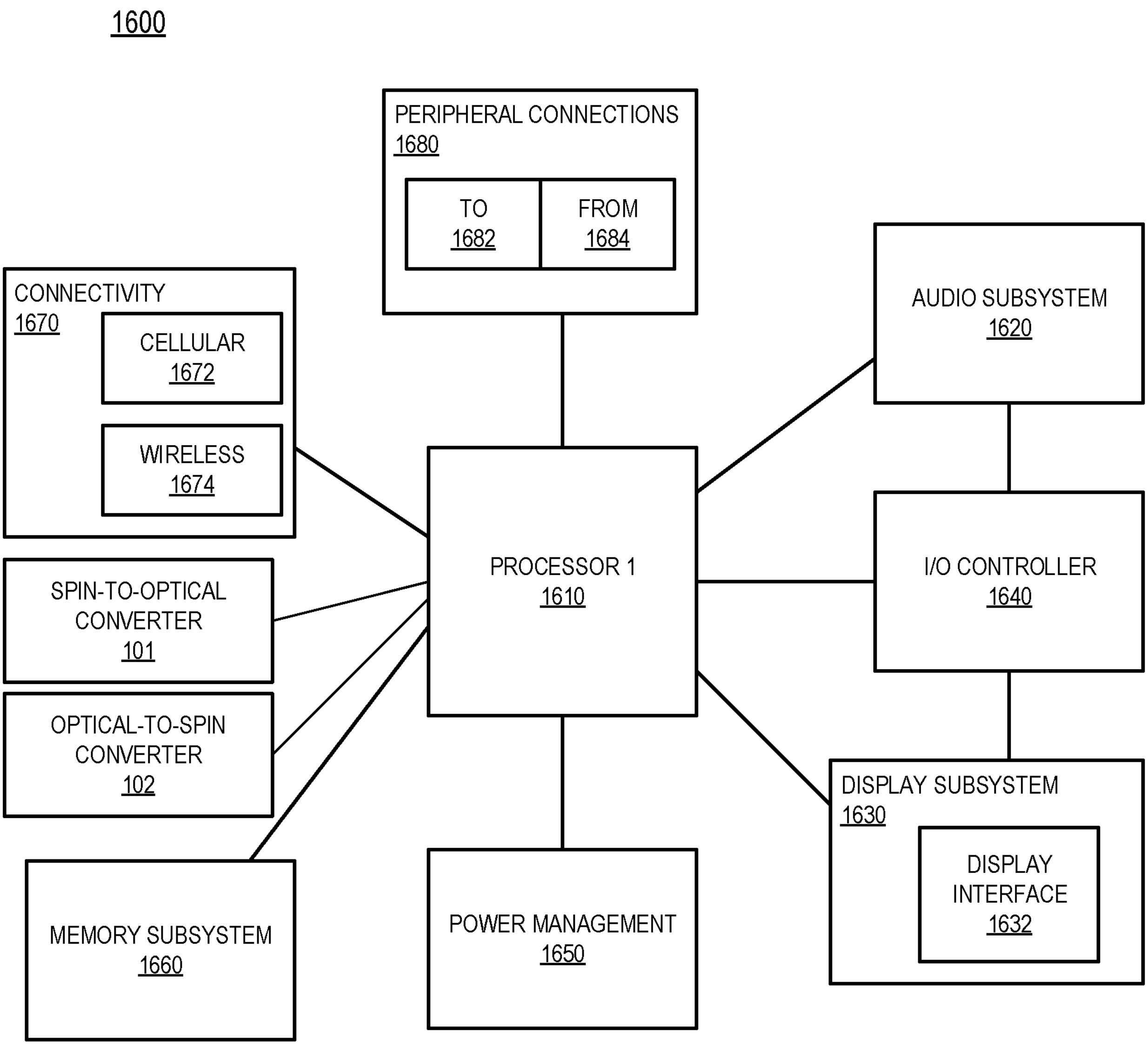
1600
PERIPHERAL CONNECTIONS
1680
TO
1682
FROM
1684
CONNECTIVITY
1670
CELLULAR
1672
WIRELESS
1674
AUDIO SUBSYSTEM
1620
PROCESSOR 1
1610
I/O CONTROLLER
1640
SPIN-TO-OPTICAL CONVERTER
101
OPTICAL-TO-SPIN CONVERTER
102
DISPLAY SUBSYSTEM
1630
DISPLAY INTERFACE
1632
MEMORY SUBSYSTEM
1660
POWER MANAGEMENT
1650

Fig. 11

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/039899

A. CLASSIFICATION OF SUBJECT MATTER

H01S 3/03(2006.01)i, H01S 3/16(2006.01)i, H01S 5/30(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01S 3/03; H01S 3/10; H01S 3/05; H01S 3/11; G02B 6/26; G02B 6/122; G02B 6/12; H01S 3/1055; H01S 3/16; H01S 5/30

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: waveguide, high spin orbit coupling material, chalcogenide, electrode, ferromagnet

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2013-0107352 A1 (CHARLES M. SANTORI et al.) 02 May 2013 See paragraphs [0011]-[0018], [0022], claims 1-3 and figures 1-3.	1,5-11,25
Y		2-4,12-24
Y	JP 2001-350039 A (TOKYO INST OF TECHNOL) 21 December 2001 See paragraphs [0019], [0023], claim 1 and figure 1.	12-24
Y	US 2012-0189026 A1 (NATHAN LORENZO BINKERT et al.) 26 July 2012 See paragraph [0036], claim 1 and figure 6.	2-4
A	US 2010-0142567 A1 (ANDREW WARD et al.) 10 June 2010 See paragraphs [0045]-[0059], claim 30 and figure 4.	1-25
A	US 2009-0263076 A1 (SAGI MATHAI et al.) 22 October 2009 See paragraphs [0027]-[0038], claim 1 and figure 2.	1-25

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search
20 February 2017 (20.02.2017)

Date of mailing of the international search report
20 February 2017 (20.02.2017)

Name and mailing address of the ISA/KR
International Application Division
Korean Intellectual Property Office
189 Cheongsa-ro, Seo-gu, Daejeon, 35208, Republic of Korea
Facsimile No. +82-42-481-8578

Authorized officer
LEE, Myung Jin
Telephone No. +82-42-481-8474

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		WO 2009-129545 A8	22/04/2010