phase shifters 123) also comprising titanium nitride (TiN) thermo-optical heaters 134 (on substrate 141) to modulate the optical phases of the optical field in the first segment waveguides connected to second segment waveguides 110. The heater heats the waveguides in second segment, and thereby modulates the refractive index of the waveguides in the second segment to shift the optical phase difference of the optical field between the beam emitters in the *y*-direction, which in turn steers the optical beam along the *y*-direction. Each thermo-optical heaters 134 may be connected to a metal structure (on the bottom layer), electrically connected to another metal structure (on the top layer) through an electrical via. Advantageously, the heating of thermo-optical heaters can be introduced by applying voltage to electrical pads electrically connected to metal structure.

[0034] Fig. 8 is a table showing a schematic top view of an embodiment of an OPA which corresponds to that in Fig. 1, having a photonic component 117 to steer optical beam in the *x*-direction (due to optical phase shifts applied to the waveguides 110 in the first segment) and 118 to steer optical beam in the *y*-direction (due to optical phase shifts applied to the waveguides 119 in the second segment) in accordance with one embodiment. The photonic component 117 is shown with optical phase shifters 122 comprising n++ (heavily doped, for example with acceptor concentration N_a = 1 x 10^{20} cm^3) doped (ion implanted) thermo-optical heaters 137 to modulate the optical phases of the optical field in the waveguides 110 perturbed by a plurality of scatterers 121 positioned along the waveguides. In contrast to the embodiment in Fig. 7, the photonic component 117 in Fig. 8 is based on heavily doped phase shifters to generate heat for optical phase shift on waveguides 110. The heavily doped phase shifters are typically placed at the sides of waveguides 110, and as a result the pitch of waveguides 110 is substantially increased. The waveguide cladding can comprise undercladding 114 and overcladding 113. The heater heats the waveguides 110 in first segment, and thereby

modulates the refractive index of the waveguides 110 in the first segment to shift the optical phase difference of the optical field between the beam emitters in the *x*-direction, which in turn steers the optical beam along the *x*-direction. The photonic component 118 is shown with optical phase shifters 123 comprising pn-junction (p doped region labelled 135, and n-doped region labelled 136) on the waveguides 119, to modulate the optical phases of the optical field in the waveguides 119. Voltage applied across the pn-junctions which forms the optical phase shifter 122 introduces plasma dispersion effect in the waveguides 119 in the second segment, and thereby modulates the refractive index of the waveguides 119 to shift the optical phase difference of the optical field between the beam emitters in the *y*-direction, which in turn steers the optical beam along the *y*-direction. The doped semiconductor structures 135, 136 and 137 may be connected to a metal structure (on the bottom layer), electrically connected to another metal structure (on the top layer) through an electrical via. Advantageously, plasma dispersion effect can be introduced from the doped semiconductor waveguide structures 135 and 136 by applying voltage to electrical pads electrically connected to metal structure. Likewise, the heating of thermo-optical heaters can be introduced from the heavily doped semiconductor structure 137 by applying voltage to electrical pads electrically connected to metal structure.

[0035] The phase shifters 122 need not extend along an entire length of the waveguides 110 in the first segment, and the phase shifters 123 need not extend along an entire length of the waveguides 119 in the second segment. The desired optical phase shift may be modified by varying the portion of the segments to which the phase shifter extends, creating an optical phase shifted region of each segment.

[0036] Fig. 9 is a table showing a partial isometric schematic view of different optical phase shifters (a highly doped semiconductor thermo-optic phase shifter 152 located at the sides of waveguides 110 in the first segment, a pn-doped semiconductor phase shifter 151 in the second segment, metal thermo-optic phase shifters in the first and second segments (154 and 153 respectively), that correspond to the optical phase shifters represented in Fig. 7 and Fig. 8) in accordance with several preferred embodiments of optical phase shifters. For example, in accordance with one embodiment of OPA, the OPA 100 can comprise rows (*M*) of metal thermo-optic optical phase shifters 154 positioned adjacent to or otherwise integrated to total internal reflection-based waveguides 119 formed from Si_3N_4 at a first segment, and separate rows (*M*) of metal thermo-optic optical phase shifters 153 positioned adjacent to or otherwise integrated to total internal reflection-based waveguides 110 and scatterers 121 formed from Si_3N_4 at a second segment. In accordance with another embodiment of the OPA, the OPA 100 can comprise first rows (*M*) of pn-doped optical phase shifters at a first segment, and separate second rows (*M*) of doped semiconductor thermo-optic optical phase shifters 151 at a second segment. Optionally, the number of rows (*M*) and column (*N*) of the OPA 100 can range between 2 to 10000, for example. The OPA 100 that comprise optical phase shifters (117 and 118), which can in turn comprise any of several different types of optical phase shifters (metal thermo-optic optical phase shifters, pn-doped optical phase shifters, pin-doped optical phase shifters, doped semiconductor thermo-optic optical phase shifters, optical phase shifters based on thermo-optic effect) adapted for use in LiDAR systems, or free-space transceivers, for example.

CLAIMS

What is claimed is:

1. An optical phased array for 2D steering of an optical beam comprising, in combination:

at least one optical waveguide having a refractive index, with each waveguide having a plurality of scatterers;

a first segment at a first optical waveguide of the at least one optical waveguide, wherein the first segment is adapted to steer the optical beam in an *x*-direction, and the first segment comprises at least one first optical phase shifter positioned below or above the first optical waveguide and the plurality of scatterers;

a second segment at a second optical waveguide of the at least one optical waveguide, wherein the second segment is adapted to steer the optical beam in a different direction than the first segment, and the second segment comprises at least one second optical phase shifter positioned below or above the second optical waveguide; and

a waveguide cladding surrounding the first optical waveguide and the second optical waveguide, wherein the waveguide cladding includes an undercladding and an overcladding, and the first optical waveguide and the second optical waveguide are connected and arranged within the overcladding.

2. The optical phased array of claim 1 wherein the at least one first optical phase shifter is different from the at least one second optical phase shifter.

3. The optical phased array of claim 1 further comprising at least one electrical

connection between the at least one first optical phase shifter in the first segment and the at least one second optical phase shifter in the second segment.

4. The optical phased array of claim 1 wherein each of the at least one first optical phase shifter and the at least one second optical phase shifter changes the refractive index of the at least one optical waveguide based on one of a thermo-optic effect, a plasma dispersion effect, an electro-optic effect, a photonic microelectromechanical system switching, or a material structural change.

5. The optical phased array of claim 4 comprises

a thermo-optic phase shifter which comprises one of a metal heater, an alloy heater, a ceramic heater, and a highly doped semiconductor heater;

a plasma-dispersion effect-based doped phase shifter which comprises one of a pn-doped and a pin-doped semiconductor;

an electro-optic effect-based phase shifter which comprises one of a Pockel's effect-based modulator and a Kerr's effect-based modulator;

a photonic microelectromechanical system switching phase shifter which comprising a microelectromechanical system switch that introduces variations in evanescent field perturbations to change the refractive index of the waveguides; or

a material structural change-based phase shifter which comprises one of a liquid crystal, a ferroelectric, and a phase change material.

6. The optical phased array of claim 1 comprising a first row of first segments and a second row of second segments, wherein the at least one first optical phase shifter in each first segment is operatively connected to the at least one second optical phase

shifter in the second segment.

7. The optical phased array of claim 1 wherein

the at least one optical waveguide comprises a plurality of waveguides, the at least one first optical phase shifter comprises a plurality of first optical phase shifters, and the at least one second optical phase shifter comprises a plurality of second optical phase shifters; and

each first optical phase shifter comprises a first layer positioned below or above each of the corresponding waveguides, and each second optical phase shifter comprises a second layer positioned below or above the each of the corresponding waveguides.

8. The optical phased array of claim 1 wherein the at least one optical waveguide and each of the corresponding scatterers comprise independently of at least one or more of Si, SiO_2 Si_3N_4, $BaTiO_3$, Li_3NbO_3, InP, a polymer, a III-V compound other than InP, and a II-VI compound.

9. The optical phased array of claim 1 wherein the at least one optical waveguide and each of the corresponding scatterers are independently doped with a p-type or an n-type material.

10. The optical phased array of claim 1 wherein each of the plurality of scatterers comprises one of Mie scatterers and Rayleigh scatterers.

11. The optical phased array of claim 1 wherein each of the plurality of scatterers

is embedded in the corresponding at least one optical waveguide.

12. The optical phased array of claim 1 wherein each of the plurality of scatterers is in contact with a top wall or a side wall of the corresponding at least one optical waveguide.

13. The optical phased array of claim 1 wherein each of the at least one optical waveguide is one of a total internal reflection-based waveguide and an in-plane scattering waveguide.

14. The optical phased array of claim 1 wherein each of the at least one optical waveguide is a rectangular waveguide having an elongate top surface and side walls extending from the top surface.

15. The optical phased array of claim 1 further comprising a controller adapted to calculate information about an object based on the optical beam.

16. The optical phased array of claim 1 having a number of rows, wherein a number of the optical phase shifters is linearly proportional with the number of rows.