Phased arrays in the optical domain that are produced to date are complex, costly and/or have a different purpose than beam forming and beam steering; some combine spatial filters, optical amplifiers and ring lasers (US 7,339,727), some involve a plurality of optical input beams (US 7,406,220), some involve volume diffraction gratings and a plurality of input directions (US 7,428,100), some combine beams of a plurality of wavelengths (US 7,436,588), some have optical phase reference sources and gain elements (US 7,489,870), some have predetermined areas in the field of view and a plurality of beam forming elements (US 7,532,311), and some have multiple frequencies and multiple optical phase reference sources (US 7,555,217).

Two-dimensional beam forming and steering phased arrays in the optical domain that are produced to date have low yields and are costly because they steer in two dimensions with a complex two-dimensional pixel array.

SUMMARY OF THE INVENTION

A one-dimensional (1D) planar beam forming and steering optical phased array chip is a simple building block of a two-dimensional (2D) beam forming and steering solid-state lidar, enabling manufacturing of said lidars at high yield and low cost through the use of a plurality of said chips. Innovative Photonic Integrated Circuit (PIC) chip architectures that follow Design for Manufacturing (DFM) rules enable said building blocks.

According to a first aspect of the present invention, there is provided an apparatus comprising: a first optical phased array one-dimensional beam forming and steering integrated circuit with a first field of view steering range adjacent to a second optical phased array one-dimensional beam forming and steering integrated circuit with a second field of view steering range, the first field of view steering range and the second field of view steering range establishing an increased horizontal field of view steering range in a common direction, the first optical phased array one-dimensional beam forming and steering integrated circuit and the second optical phased array one-dimensional beam forming and steering integrated circuit each being a building block of a solid-state lidar, and each including: at least one optical power splitter; and at least one optical phase shifter controlled with at least one phase shifting device, including but not limited to: a gain element, an all-pass filter, a Bragg grating, a dispersive material, a wavelength tuning device and a phase tuning device.

There is disclosed a method for optical-phased-array-based one-dimensional beam forming and steering utilizing a photonic integrated circuit apparatus comprising: at least one optical power splitter; at least one optical phase shifter; and at least one out-of-plane optical coupler laid out in a pixel array configuration.

DESCRIPTION OF THE DRAWINGS

The following drawings are illustrative of embodiments of the present invention and are not intended to limit the invention as encompassed by the claims forming part of the application.

The schematic diagram of Figure 1 depicts the splitting section of a 1D planar beam forming and steering optical phased array chip, said splitting section comprising a 1xL Y-branch tree **20** followed by 1xM multimode interference couplers **30**, resulting in a 1xN splitter (where LxM=N, e.g., 8x128=1024).

The schematic diagram of Figure 2 depicts a 1D planar beam forming and steering optical phased array chip, said chip comprising a laser **10**, a splitting section comprising a Y-branch tree **20** and multimode interference couplers **30**, optical phase shifters **40**, and out-of-plane optical couplers **120** laid out in a one-dimensional pixel array configuration. A graded-index (GRIN) lens **140** is used to reduce the spot size in the dimension perpendicular to the steering direction. Alternatively, a standard geometric refractive lens, a diffractive optical

What is Claimed is:

1. An apparatus, comprising:

a first optical phased array one-dimensional beam forming and steering integrated circuit with a first field of view steering range adjacent to a second optical phased array one-dimensional beam forming and steering integrated circuit with a second field of view steering range, the first field of view steering range and the second field of view steering range establishing an increased horizontal field of view steering range in a common direction, the first optical phased array one-dimensional beam forming and steering integrated circuit and the second optical phased array one-dimensional beam forming and steering integrated circuit each being a building block of a solid-state lidar, and each including:

at least one optical power splitter; and

at least one optical phase shifter controlled with at least one phase shifting device, including but not limited to: a gain element, an all-pass filter, a Bragg grating, a dispersive material, a wavelength tuning device and a phase tuning device.

2. The apparatus of claim 1 further comprising at least one on-chip gratingor at least one off-chip lens.

3. The apparatus of claim 2 wherein said at least one off-chip lens includes but is not limited to: a refractive lens; a graded-index lens; a diffractive optical element and a holographic optical element.

4. The apparatus of claim 1 wherein said at least one optical power splitter is selected from any subset of power splitting optical devices, including but not limited to:

Y-branches;

Directional couplers; and

Multimode interference couplers.

5. The apparatus of claim 4 wherein said at least one optical power splitting has Y-branches followed by multimode interference couplers.

6. The apparatus of claim 1 wherein an actuation mechanism of said at least one phase shifter utilizes a subset of actuation mechanisms, including but not limited to:

Thermo-optic actuation;

Electro-optic actuation;

Electroabsorption actuation;

Free carrier absorption actuation;

Magneto-optic actuation;

Liquid crystal actuation; and

All-optic actuation.

7. The apparatus of claim 1 wherein each pixel of the pixel array has associated with it an independent phase shifter.

8. The apparatus of claim 1 wherein a plurality of said pixels of the pixel array are banded by having combined phase shifters.

9. The apparatus of claim 8 wherein the plurality of pixels of the pixel array are banded with control elements, including but not limited to one or a plurality of the following:

linear electrodes;

nonlinear electrodes; and

phase offset electrodes.

10. The apparatus of claim 9 wherein electrodes present in plural quantities are disposed in a manner that is at least one of the following:

Serial;

Parallel;

Additive; and

Subtractive.

11. The apparatus of claim 1 combined with at least one out-of-plane optical coupler achieved with an optical element including but not limited to:

Gratings;

Holographic optical elements;

Mirrors;

Total internal reflection interfaces; and

Lenses.

12. The apparatus of claim 1 combined with a lensing apparatus to extend the steering range.

13. The apparatus of claim 1 wherein said photonic integrated circuit is compatible with a complementary metal-oxide-semiconductor silicon fabrication process.