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FMCW LiDAR Incorporating Slow-Light Grating Beam Scanners

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Abstract *Slow-light grating based on photonic crystal waveguides, fabricated by standard silicon photonics process, allows electrically driven completely nonmechanical 2D beam scanning with high resolution and wide field of view. It is incorporated in an integrated FMCW LiDAR chip and real time LiDAR operation is obtained.*

Introduction

Light detection and ranging (LiDAR) systems are being developed extensively as 3D sensors in autonomous vehicles and in many other applications. Furthermore, frequency-modulated continuous-wave (FMCW) LiDAR is attracting particular attention because of various advantages, compared with time-of-flight (TOF) LiDARs, such as high sensitivity and low crosstalk due to its coherent detection, and the imaging of motion such as velocity and vibration from Doppler shifts which evolves LiDAR systems to be 4D sensors. Figure 1 summarizes various application fields of 3D/4D LiDAR.

To simplify the fabrication of FMCW's complicated optical receiver circuit, Si photonics integration technology has been applied. Moreover, if it also enables electrically driven completely nonmechanical beam scanning in the same photonic integration platform, a full on-chip, compact, fast, and flexible FMCW LiDAR will become possible. For this purpose, the optical phased array (OPA) [1,2] has extensively been studied, although it is challenging on the points of ultra-large-scale photonic integration and calibration, high resolution and sensitivity, and low power consumption. The focal plane array (FPA) [3,4] has also attracted attention because it simplifies the calibration and achieves a high sensitivity with a lens for projection and condensation although the challenging for the ultra-large-scale photonic integration and wide field of view (FOV) remains.

The slow-light grating (SLG) based on photonic crystal waveguides (PCWs), which can be fabricated by a standard Si photonics foundry service, is an alternative device [5–7]. Compared with the above two, it achieves

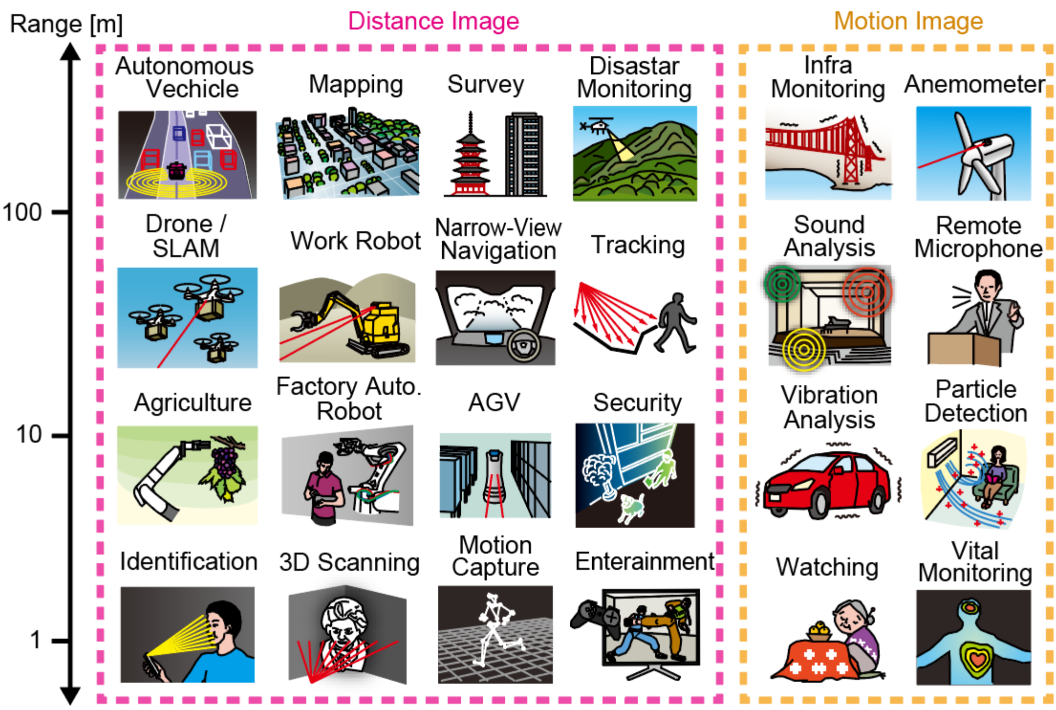

Fig. 1 Application fields of 3D/4D LiDAR sensors. [7]

high-resolution and wide FOV of the scanned beam simultaneously with a lower integration scale. It uses thermo-optic beam scanning, which does not require a wavelength-swept laser source but a fixed wavelength laser such as DFB laser diodes and allows a beam scanning time of several μs [8]. Integrated with a FMCW receiver circuit, it showed the LiDAR action.

This presentation provides an overview of recent LiDAR development and the above challenges for a fully integrated LiDAR chip. Featuring SLG devices, I discuss the pros and cons of these approaches, their status and future potential.

SLG

The SLG consists of PCWs with surface gratings. A slow-light mode guided in the PCW is radiated to the free space as a fan-shaped beam due to a long radiation aperture and narrow modal field along and across the PCW, respectively. The length of the PCW and radiation rate are typically set at 1.5 mm and 100 dB/cm, respectively, for which the beam divergence in the θ direction along the PCW is less than 0.08° at $\lambda \approx 1550$ nm. The slow-light mode largely changes its propagation constant β for a small change of λ and/or PCW's refractive index. Then, the scanning range $\Delta\theta$ = 20°–30° is obtained for the wavelength change $\Delta\lambda$ = 25 nm and the thermo-optic effect with a temperature increase ΔT = 300–400 K; the corresponding wavelength and temperature sensitivity of θ is approximately 1.0°/nm and 0.07°/K. The beam scanning in the range of This range is determined by the slow-light band sandwiched by the band-edge and light line, but this $\Delta\theta$ can be doubled to 40°–60° when the direction of light propagation in the waveguide is switched. Since the above temperature increase is acceptable for Si photonics devices, the thermo-optic SLG can be an electrically driven completely nonmechanical beam scanner. In this case, we can use a standard DFB laser, as mentioned above. This is an important merit in FMCW LiDAR for which a narrow linewidth laser light is particularly desired in sensitive coherent detection.

The emitted beam is fan-shaped due to the strong lateral confinement of the slow-light mode in the PCW but can be converted into a spot beam using a bespoke prism lens, which maintains the collimation condition for different θs. If many of such SLGs are integrated in parallel and light is launched on one of them via waveguide switching, the offset of the SLG against the center of the lens produces a tilt angle $\Delta\phi$ in the direction across the PCW. Combining $\Delta\theta$ and $\Delta\phi$, the 2D beam scanning is obtained.

Fabrication and operation

Figure 2 shows an FMCW LiDAR chip and demonstrates its operation. The chip incorporated the SLG beam scanner and FMCW receiver circuit including Ge photodiodes. The FMCW LiDAR experiment was performed with this chip and external laser source and $LiNbO_3$ I/Q modulator for single sideband modulation; we did not used a Si I/Q modulator integrated on the same chip due to insufficient performance, but the on-chip modulator is expected to be used in future. Round-trip light between the LiDAR chip and objects was mixed with local reference light to produce a beat frequency as a range signal

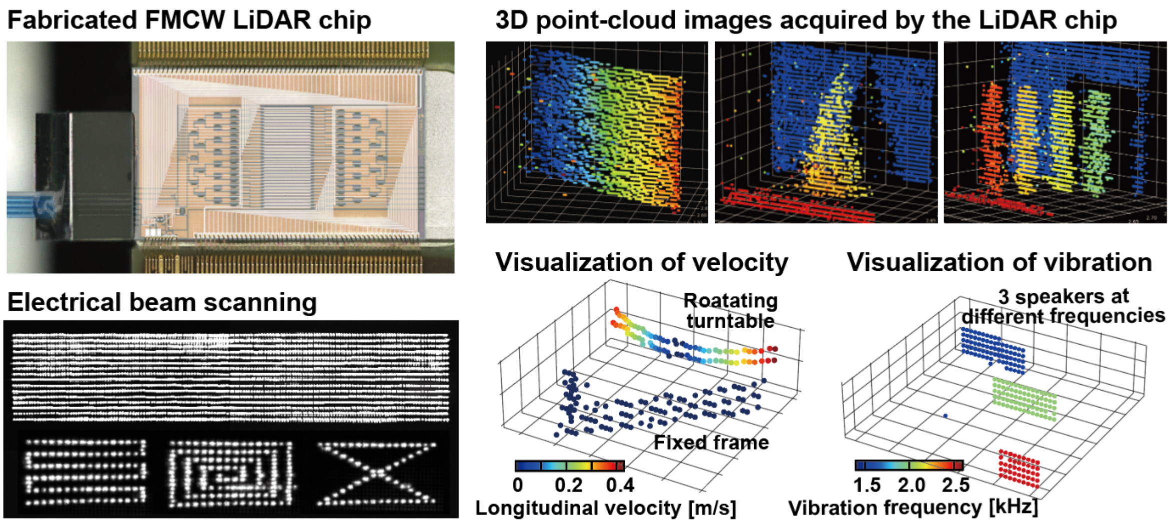

Fig. 2 Fabrication of FMCW LiDAR chip and demonstration of full electrical beam scanning, acquisition of point cloud images and velocity and vibration imaging [5,7,9].

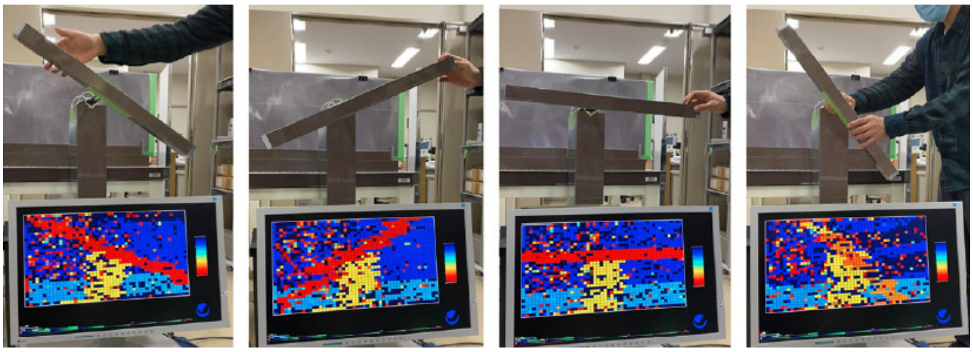

Fig. 3 Realtime demonstration of FMCW LiDAR chip, which are driven and signal-analyzed using FPGA circuits [7].

via the delay homodyne coherent detection and an FPGA FFT circuit. Emitting and scanning frequency-swept laser beam, point cloud images of 154 × 32 = 4928 points were obtained. The real-time operation with a speed of over 10 fps was obtained by reducing the number of points, as shown in Fig. 3. The velocity and vibration imaging were also demonstrated using a turntable and speakers as targets [7,9].

In this experiment, we covered these targets with a retroreflective film to compensate for insufficient S/N of the range signal. But we estimated that the device can detect Lambertian targets over long distances in the 100-m class by reasonably reducing chip and optics losses, suppressing internal noise components, and increasing the effective reception aperture in a serial array configuration [10].

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