Integrated Optical Beam Scanning and FMCW Ranging using Multiplexed Tunable Lasers

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2022 IEEE Photonics Conference (IPC) | 978-1-6654-3487-4/22/$31.00 ©2022 IEEE | DOI: 10.1109/IPC53466.2022.9975452

Abstract

We extend the concept of the (pixellated) dispersive optical phased array with multiplexed tunable laser sources and show that these can at the same time be used for frequency-modulated continuous-wave (FMCW) distance and velocity measurements.

Index Terms

Optical phased arrays, LiDAR, ranging, frequency-modulated continuous-wave, FMCW

I. Introduction

LiDAR (Light Detection and Ranging) has turned into a hot research topic, with important applications in autonomous vehicles (cars, drones), security and metrology [1]. The optical engine of a LiDAR has two main functions: ranging (measuring distance to remote objects) and beam steering. The long-term vision is that these can be integrated in a solid-state system, and for beam steering the primary candidates are focal-plane arrays and optical phased arrays (OPA) [2]. The latter present more engineering challenges but are considered to be the more flexible long-term solution, especially when integrated on a chip.

Optical phased arrays consist of a multitude of antennas that emit light with a controlled phase delay, which determines the direction of the composite beam. For 2D beam steering, one can use a 2D array of antennas (e.g. grating couplers), or a 1D array of antennas (along x) where the steering in the other direction (y) is controlled by the laser wavelength [3]. The phase delay for the steering along x can be induced by electro-optic phase shifters, but this can become challenging for large numbers of densely-packed antennas. Alternatively, one can induce a linear phase ramp using dispersive delay lines, which makes it possible to scan the far field in both x and y directions with the wavelength of the laser [4]. However, this technique also has scaling limitations for large arrays, which is the reason we introduced a pixellated version of this dispersive OPA that still scales up to thousands of antennas [5], simply by scanning the wavelength of the laser.

For the ranging function, the implementations are divided into pulse-based ranging and coherent detection, usually through a frequency-modulated continuous-wave (FMCW) scheme [1]. By sweeping the frequency of the emitting laser, and interfering it with the return signal, the mixed difference frequency is an accurate measure of the distance. As a bonus, the technique can also measure radial velocity thanks to the Doppler effect. The frequency sweep can be implemented by electro-optic modulation, but a more simple approach is to sweep the laser wavelength.

In this paper, we present a concept where we sweep the laser wavelength to implement both the FMCW ranging and the 2D beam steering. Based on the required angular resolution, frame-rate and acquisition time, we show that we will need to multiplex different lasers, but that this can be elegantly integrated into the same LiDAR engine.

II. 2D Optical beam scanning with a swept tunable laser

We base our calculation on the OPA dimensions we proposed earlier in [5]. This pixellated OPA covers a $25° \times 12°$ field of view with an angular resolution of $0.1°$. This amounts to 30,000 pixels in the far field, which are scanned by sweeping the laser from $1500\,\mathrm{nm}$ to $1600\,\mathrm{nm}$. If we assume a frame rate of $25\,\mathrm{Hz}$ to scan the full field, the laser should be swept with $300\,\mathrm{GHz/ms}$. In this sweep, each pixel would be illuminated during $t_{pixel} = 1.33\,\mathrm{\mu s}$, which corresponds to a frequency range of $400\,\mathrm{MHz}$ of the laser.

III. FMCW ranging with a swept tunable laser

FMCW ranging is based on a linear frequency sweep of the emitting laser. After the emitted beam has bounced off a remote object, it is interfered with the local laser light (local oscillator), which will have shifted in frequency by that time. From the resulting beat frequency, the travel time can be calculated. If the remote object is moving towards or away from the LiDAR engine, the return light will experience an additional Doppler shift. To disentangle the effect of the range and the relative velocity, the laser frequency (wavelength) is swept in both directions. FMCW ranging needs a tunable laser with a sufficiently narrow linewidth (kHz) to have a coherence length compatible with the range of the LiDAR. In this case, we assume the requirement of $200\,\mathrm{m}$ for forward-looking automotive LiDAR. The scanning rate also needs to be adjusted such that the electronics can easily measure the beat frequency. For sufficient axial resolution ($10 - 20\,\mathrm{cm}$), a sweep rate corresponding

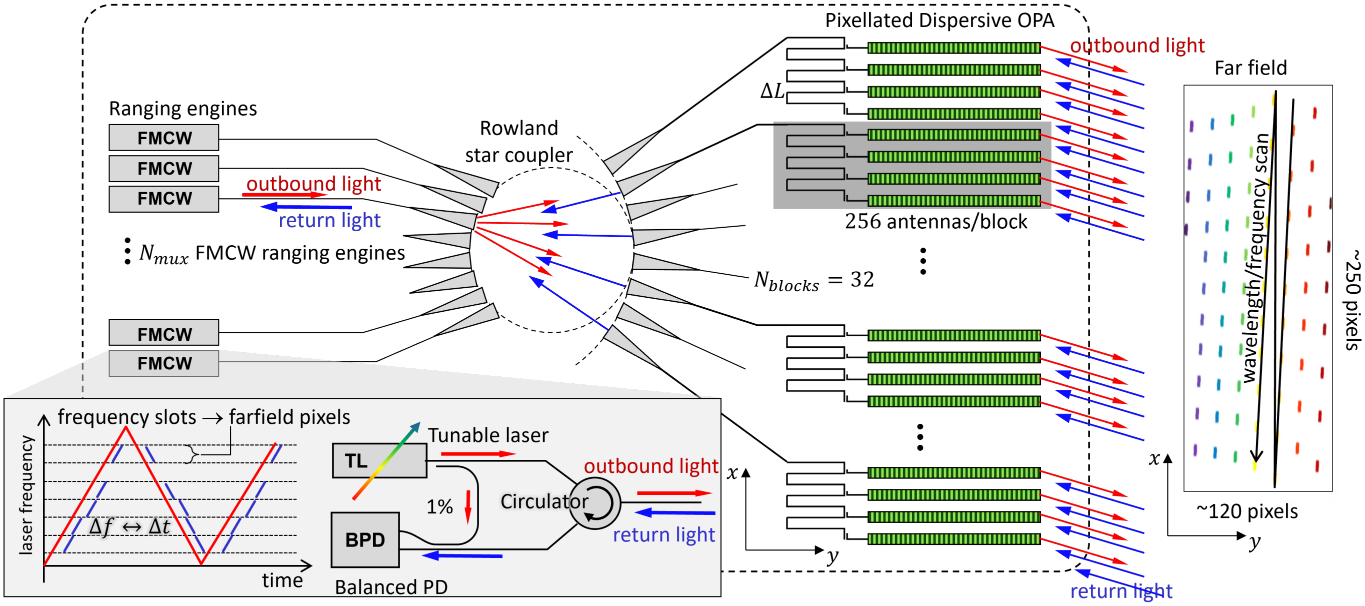

Fig. 1. Conceptual schematic of the multiplexed 2D pixellated dispersive OPA beam scanner with an FMCW ranging engine.

to $> 100\,\mathrm{kHz/m}$ distance, or $> 60\,\mathrm{GHz/ms}$ would be sufficient. This sweep rate also influences the acquisition time, as the laser should dwell sufficiently long on the target to generate a return signal long enough to measure the beat frequency. In this case, a time of $t_{pixel} = 50 - 100\,\mu\mathrm{s}$ would be needed per illuminated pixel.

IV. Multiplexing Lasers

There is a clear mismatch between the requirements of the FMCW ranging and the beam scanning OPA. However, these can be reconciled if we multiplex multiple ranging engines (each with its own tunable laser) into the OPA. The pixellated dispersive OPA provides a very elegant mechanism to perform this multiplexing with minimal losses. The architecture in [5] has a 1×32 splitter tree, which can be replaced with a slab waveguide star coupler. It is now possible to add multiple (off-center) input apertures to this star coupler on a Rowland circle. Each of these apertures can be fed with its own ranging engine. Because the off-axis injection in the star coupler also introduces an additional phase delay, they will illuminate different positions in the far field. If we use N_{mux} inputs, we are effectively measuring N_{mux} pixels in the far field simultaneously, so we can now reduce the scan speed of each engine with the same factor. The difference between t_{pixel} in the OPA calculation and in the FMCW requirements suggests that we need at least $N_{mux} \approx 32$.

The multiplexing offers an additional advantage: we can combine multiple light sources that each cover only a fraction of the full wavelength range. This is extremely useful, because for good FMCW range we preferably have a mode-hop-free tunable laser. By splitting up the full wavelength range in $N_{laser} = 32$ segments of $400\,\mathrm{GHz}$, this tuning range is well within the capabilities of integrated semiconductor lasers. This calculation suggests that $N_{mux} = N_{laser} = 32$ might suffice, but we need to include at least another $\times 2$ factor, because for FMCW ranging we need at least one upward and one downward frequency scan to disentangle the distance from the Doppler shift.

V. Conclusion

We presented a concept for an optical LiDAR engine (beam scanning + ranging) that is fully driven by a bank of tunable lasers. The entire photonic circuit can in principle be constructed in a passive photonic chip technology, with the constraints that it requires compact waveguides with low propagation loss ($10\,\mathrm{dB/m}$ would be acceptable) and low phase fluctuations.

References

[1] B. Behroozpour *et al.* "Lidar system architectures and circuits," *IEEE Communications Magazine*, vol. 55, no. 10, pp. 135–142, 2017.

[2] M. J. Heck, "Highly integrated optical phased arrays: photonic integrated circuits for optical beam shaping and beam steering," *Nanophotonics*, vol. 6, no. 1, pp. 93–107, 2017.

[3] K. V. Acoleyen *et al.* "Off-chip beam steering with a one-dimensional optical phased array on silicon-on-insulator," *Opt. Lett.*, vol. 34, no. 9, pp. 1477–1479, 2009.

[4] K. V. Acoleyen *et al.* "Two-dimensional dispersive off-chip beam scanner fabricated on silicon-on-insulator," *IEEE Photon. Technol. Lett.*, vol. 23, no. 17, pp. 1270–1272, 2011.

[5] W. Bogaerts *et al.* "A 2D pixelated optical beam scanner controlled by the laser wavelength," *IEEE J. Sel. Top. Quantum Electron.*, vol. 27, no. 1, pp. 1–12, 2021.