Analysis of the Principle and State-of-art Applications of Si-Based Chip on Lidar

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Abstract. In recent years, as the feature size of transistors continues to decrease, Moore's Law is also approaching its limits. On this basis, In the post-Moore era, optical interconnect technologies with inherent attributes such as low latency, low power consumption, and low crosstalk have gained widespread attention in the industry. Silicon photonics technology has emerged, leveraging the accumulated knowledge from the silicon-based microelectronics industry over half a century. Optical phased arrays, unlike traditional mechanical-based lidar systems, offer advantages such as small size, low cost, and high accuracy. When combined with mature CMOS processes, they hold significant research value and market prospects. With this in mind, this study will discuss the principle as well as the state-of-art applications for Si-based chip on Lidar. According to the analysis, the current limitations are also demonstrated and suggestions are proposed based on the evaluations. Overall, these results shed light on guiding further exploration of chip developments on Lidar.

Keywords: Silicon photonics technology, optical phased array, integrated optics, integrated optoelectronic devices.

1. Introduction

Over the past half-century, silicon-based microelectronics has achieved tremendous success. However, as the feature size of transistors continues to decrease, integrated circuit interconnects face limitations such as high power consumption, significant signal crosstalk, heat generation, processing difficulties, and significant quantum effects. As a result, the semiconductor industry is gradually entering the post-Moore era. Therefore, optical interconnects with inherent attributes such as high bandwidth, low latency, low power consumption, and low crosstalk have become one of the research hotspots in the post-Moore era.

With in-depth research on various semiconductor materials, the fields of microelectronics and optical communications have gradually merged, forming a cross-disciplinary field represented by optoelectronics. Integrated photonics has rapidly developed over the past half-century. Silicon photonics technology combines the advantages of CMOS (Complementary Metal-Oxide-Semiconductor) technology with its large-scale logic and ultra-high precision manufacturing characteristics, as well as the high-speed and low-power capabilities of photonics technology. It has garnered widespread attention in the industry since its inception [1].

As the most basic raw material for achieving modern oversized integrated circuits, silicon is both an electronic material and a photon material. British scientist Canham discovered in 1990 that it can produce visible light in high-efficiency real estate oxidized in the anode oxidized, and its efficiency is 100,000 times that of body silicon materials, marking the beginning of the research of silicon optical scholarship [2]. IBM has been studying the CMOS integrated photon technology since 2003. The main research results include the preparation of various photon devices required by Silicon optical interconnection technology, such as the GERMANIUM Detectors Optical waveguide, edge coupling, and optical/electrocomputers. A large number of related research papers were published in related research. Intel's Sunny California laboratory has started research on silicon-based optical interconnection technology since 2004. The main research content covers various high-quality components required for silicon -based optical interconnection, such as silicon optical controller, silicon RAMAN laser, silicon-based photons, silicon-based photons [2]. ADVA started the SPEED project funded by the German Federal Ministry of Education and Research in 2016 to create a unified

platform for development, manufacturing and packaging special silicone optoelectronic integrated chips. A new nuclear processor ATAC architecture studied by the MIT Carbon project, which uses optical technology to achieve a bus-type global broadcast network.

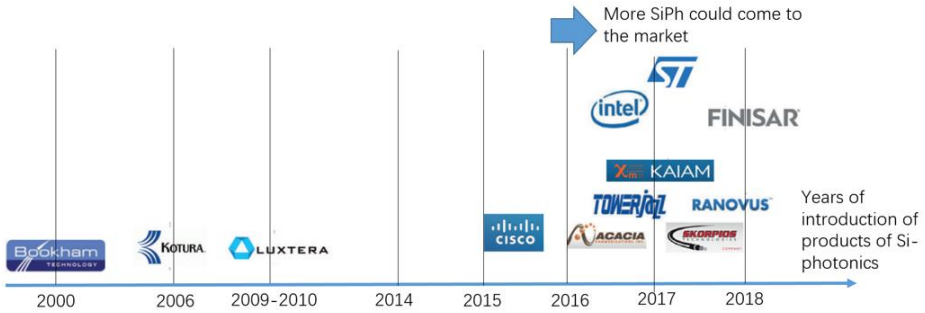


Figure 1. Current Situation of Silicon Photonics Industry

At this stage, on the silicon-based optical platform, the optoelectronic simulation matrix operation is performed through the class Maich-Zeng Del interference (MZI), which is one of the most feasible and most common practices (seen from Fig. 1). Under the existing silicon-based optical electronic device preparation process, prepare transmission loss <1DB/cm silicon -based optical waveguide, and at the same time, with a passive modulation method such as hot light, a large-scale, low-loss grade MZI optical transmission network can be achieved, and it can also be achieved. It has made richer progress in theory and experiments in the theories and experiments of the matrix mapping, network architecture, training algorithms and classification applications [3]. In terms of photoelectric analog functional operation devices, Fig. 2 is a full-optical time domain integror designed for Ferrera et al. [4]. By preparing a high -quality factor micro -ring resonant with a radius of 47.5μm on the silicon-based optical electronic chip to achieve ~ 500GHz physical physics Bandwidth and 8PS time resolution full-optical sconators have important application potential in ultra-high-frequency microwave radio frequency signal synthesis and information processing.

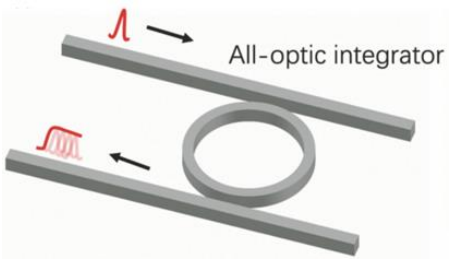


Figure 2. All-optical temporal integrator with -500GHz bandwidth and 8 ps tempora; resolution can be realized by using high-Q micro-ring resonator on silicon optoelectronic chips

Mechanical lidar, MEMS lidar, and complete solid lidar are the three types of lidar. Since the silicon-based microelectronic technology can be used to achieve single-chip integration for the various electrical drive chips, algorithm processing and imaging chips, and even the light detection needed by the silicon-based lidar, it is one of the current research directions. The phase control array laser radar mainly uses the optical phase control array (OPA) technology to achieve beam scanning. The laser light source enters the optical phase control array after the light beam device. It changes the phase of the optical waves by changing the phase of the optical waves by adding control on the phase control array. The light wave phase difference is used to achieve beam scanning. A silicon-based optical switch array laser radar is achieved by transmitting the light emitted by the laser through an optical switch array on a silicon substrate to a specific location on an optical antenna, and utilizing a lens placed above the antenna to deflect the beam. The lens is positioned at a distance equal to one focal length above the optical antenna. According to the focal plane theorem, parallel light from different directions in space converges on the focal plane when passing through the lens, focusing onto a specific location on the optical antenna [5].

Since the invention of Silicon Optic Technology at the beginning of the 20th century, its research and application have advanced quickly, its performance has continued to advance, and the application scenarios are continuously growing. Integrated circuit technology and silicon-based optical electronic technologies are both fully compatible. It can integrate electrical control logic circuits and beam scanning devices on a single chip, which is helpful for achieving intelligent control and neural network integration. Although the traditional mechanical laser radar is more developed, its high cost, difficult assembly and debugging, and limited mechanical component life span prevent it from being produced and used on a wide scale in the market. However, the Microelectronics System (MEMS) laser radar cannot be used in the field of autonomous driving due to its complexity, limited scanning efficiency, and significant environmental impact. Other types of lidar also have some difficulties in application. Therefore, silicon-based optical phase control array laser radar is one of the most cutting-edge research hotspots in recent years. Many scientific research units and high -tech companies such as MIT, the University of California, Santa Barbara, University of Texas Austin, Columbia University, Analog Photonics, Voyant Photonis, Intel, etc. carry out related research and achieve good results.

Silicon-based laser radar can greatly reduce production costs, thus it is bound to promote the development of unmanned driving, automation, artificial intelligence, astronomy, communication and other fields. Optical phase control array technology is a low inertia non -mechanical scan, which is now in the R & D stage. Due to its scanning characteristics such as flexibility, fast scanning speed, and high angle-driven scanning characteristics, and it is easy to achieve miniaturization, integration, and multi-functionalization, it has attracted much attention from various countries [6]. Because the optical phase control array radar has the above advantages, this thesis will analyze and discuss the silicon-based optical phase control array technology. The framework of this thesis is as follows. The Sec. 2 introduces the principles of optical phase control arrays and optical phase control arrays of lidar. Related performance indicators, the Sec. 3 is other applications of optical phase control arrays, Sec. 3 is silicon -based optical phase array limitations and prospects, Sec. 5 is the summary.

2. Basic Descriptions of Optical Phased Array Lidar

2.1. Basic Principle

One-dimensional or two -dimensional array composed of phase modulator units is called optical phase array device. The principle of optical phase array is similar to the working principle of prisms that takes off the beam. A beam of laser incident into the optical phase array device. By controlling the phase displacement of each phase modulation unit, the phase of the output of the optical waves of each unit is the same in the direction of the θs, so as to achieve the phase interference in this direction and generate in this direction. A beam is a high-strength beam; at the same time, the phase of the output light of each unit is interfered in other directions. The results of interference offset each other, and the radiation strength is close to zero (seen from Fig. 3) [6].

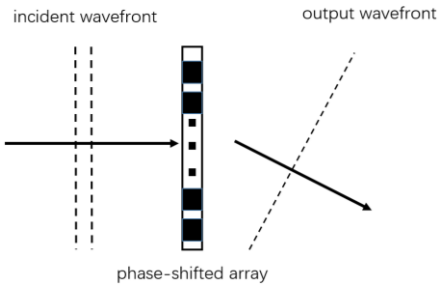


Figure 3. A sketch of the principle for optical phased array Lidar

2.2. Optical Phase Array Laser Lidar Working Principle

A combination of optical beam scanning system and a passive capture sensor based on optical phase arrays can constitute a variety of phased array lidar systems. Fig. 4 is a system principle brief

diagram of the system principle of one-dimensional phase array lidar. The phase control array lidar is a active imaging system that uses near -infrared wavelength laser as a detection carrier. The target of the target of the target of the target to the target of the target is determined by the target of the target, the reflection intensity of the target of the laser, etc. data. Lidar uses a direct detection method to use multiple sensors and programmable optical phase arrays scanning technology to realize the imaging of the area, and obtains the target details through the interpretation of the image [7]. The summary of the performance parameters of the Silicon-based integrated optical phase arrays currently reported is given in previsou study [8, 9].

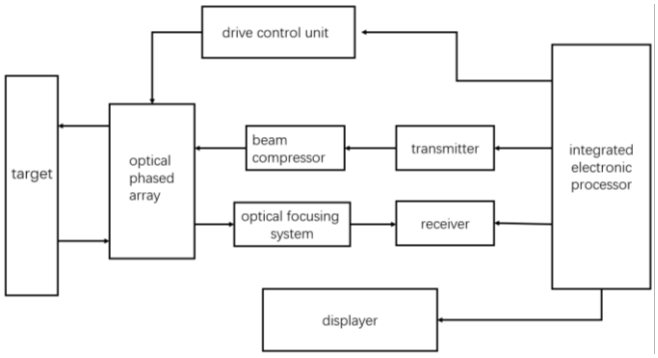


Figure 4. A system principle brief diagram of the system principle of one -dimensional phase array lidar

3. Other Applications of Optical Phased Arrays

Applications for optical phased array (OPA) technology include compensating for atmospheric turbulence, large-angle beam guiding, and creating high-brightness light sources, among others.

3.1. Compensating for Atmospheric Turbulence

In the 1970s, Hughes Re-search Laboratory in the United States first applied the array beam phase control technology to the atmospheric turbulence compensation experiment. This is called coherent optical adaptive techniques (COAT) [10]. In 2011, based on a 7-channel adaptive fiber collimator array, the University of Dayton and Army Laboratory achieved coherent synthesis of the target at a transmission distance of 7km [11] (as shown in Fig. 5). When the phase-locking system was closed-loop, there was a significant increase in the power of the far-field spot in the bucket, indicating that all phase errors caused by factors between the seed source and the target were effectively corrected.

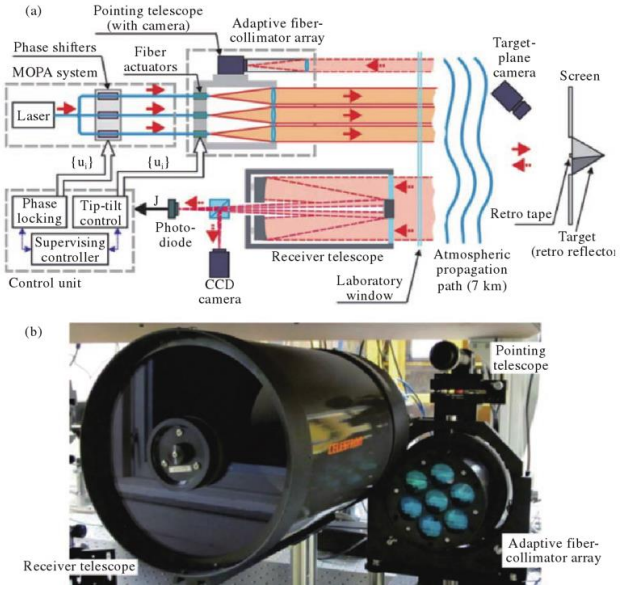


Figure 5. Schematic and photo of 7km target-in-the-loop coherent beam combination

3.2. Large-angle Beam Steering

The earliest traceable implementation of optical phased arrays using silicon-based microelectromechanical systems (MEMS) can be attributed to the 16-element optical modulator array developed by Petersen at IBM Laboratories in the United States in 1977 [12]. In 2018, Wang et al. from the University of California, USA, achieved a 160x160 array optical phased array using MEMS technology [13, 14]. The array size was 3.1mm x 3.2mm, with a beam scanning field of view of 6.6° x 4.4°. The response time was 5.7μs. For the first time, they simultaneously implemented multiple functionalities such as high optical efficiency, wide wavelength operation, fast response time, and large beam deflection angles on the same optical phased array device.

3.3. Constructing a high brightness light source

The research on fiber laser coherent synthesis technology began in the early 20th century. In 2003, the United States' Nufern Corporation and the Massachusetts Institute of Technology (MIT) initiated the research on fiber laser coherent synthesis technology. They independently achieved coherent synthesis of four 1-watt channels and two 10-watt channels using fiber lasers [15, 16]. In 2015, Lincoln Laboratory achieved coherent combining of 42 high-power fiber lasers [17], resulting in a total output power of 44kW and beam quality close to the diffraction limit. This represents the highest coherent combining efficiency of fiber lasers achieved internationally to date.

4. Limitations

Currently, silicon-based integrated photonics phased array technology still needs to address several issues [9]:

- Scanning Angle: The maximum lateral scanning angle of current optical phased arrays (OPAs) is around 80°, while the maximum vertical scanning angle is approximately 36°.
- Sidelobes: For chip-scale lidar systems based on the Fraunhofer diffraction effect, sidelobes that affect scanning quality may occur if the spacings between individual input waveguides are equal and larger than half the wavelength. In 2017, Komljenovic et al. studied sparse and non-uniformly spaced waveguide phased arrays and proposed placement schemes that effectively suppress sidelobes while ensuring a sufficiently small beam angle [18].
- Scanning Accuracy: The scanning accuracy is related to the far-field spot size of the optically controlled phased array. Traditional single-crystal silicon waveguide structures have compact volumes, large thermo-optic coefficients, and relatively easy phase modulation. However, they have a smaller tolerance for manufacturing errors, which hinders precise phase control.
- Detection Distance: When a laser is being propagated, it interacts with molecules, airborne particles, and the surfaces of objects being detected. This causes phenomena like absorption, scattering, reflection, diffraction, and refraction. Additionally, due to the effects of atmospheric turbulence, the coherence and intensity of the backscattered laser signal are altered.
- Process of Manufacturing: Chip-scale integrated phased array lidar systems have more demanding manufacturing needs. Fixed phase discrepancies between the waveguides are necessary to achieve phase interference.

5. Conclusion

To sum up, silicon-based optical phased array is intriguing. It overcomes the drawbacks of previous mechanically scanned systems and offers advantages such as high performance, low cost, small size, compatibility with CMOS technology, and ease of integration. Although there are currently challenges regarding low laser power and small aperture size, with the ongoing research by scientists worldwide, it holds vast application prospects.

References

[1] Wu B B, Zhang H Y, Tang X H, et al. Research on silicon photonics technology and industrial development. World Telecom, 2017, 30 (2): 36-41.

[2] Qian L, Wu D, Xie X H. Research on on-chip optical interconnection technology based on silicon photonics. Computer Science, 2012, 39 (5): 304-309.

[3] Harris N C, Carolan J, Bunandar D, et al. Linear programmable nanophotonic processors. Optica, 2018, 5 (12): 1623-1631.

[4] Ferrera M, Park Y, Razzari L, et al. On-chip CMOS-compatible all-optical integrator. Nature Communications, 2010, 1: 29.

[5] Wang P F, Luo G Z, Pan J Q. Silicon-based integrated LiDAR technology. ZTE Technology Journal, 2020.

[6] Ye Z Y, Zhao S S, Wang Z Y. Optical phased array technology applied to LIDAR. Opto-Electronic Engineering, 2012, 39 (02): 81-86+93.

[7] Dong G Y, Zheng Y C, Zhang W P, et al. Phased array LiDAR technology. Infrared and Laser Engineering, 2006, S3: 289-293.

[8] Zhang Y Y, Wang R, Jiang R T, et al. Performance evaluation method for silicon-based optical phased array. Applied Optics, 2021, 42 (02): 242-246.

[9] Zhuang D W, Han X C, Li Y X, et al. Research progress on silicon-based optoelectronic integrated photonic phased arrays. Laser & Optoelectronics Progress, 2018, 55 (05): 7-17.

[10] Bridges W B, Brunner P T, Lazzara S P, et al. Coherent optical adaptive techniques. Applied Optics, 1974, 13 (2): 291-300.

[11] Weyrauch T, Vorontsov M A, Carhart G W, et, al. Experimental demonstration of coherent beam combining over a 7km propagation path. Opt Lett, 2011, 36 (22): 4455-4457.

[12] Petersen K E. Mircomechanical light modulator array fabricated on silicon. Appl Phys Lett, 1977, 31: 521.

[13] Wang Y, Zhou G, Zhang X, et al. 2D broadband beamsteering with large-scale MEMS optical phasedarray. Optica, 2019, 6 (5): 557-562.

[14] Wang Y, Zhou G, Zhang X, et al. 160×160 MEMS-based 2-D optical phased array. CLEO, 2018: SM3I.

[15] Anderegg J, Brosnan S, Weber M, et al. 8-watt coherently phased 4-element fiber array. Proc of SPIE, 2003, 4974: 1-5.

[16] Augst S J, Fan T Y, Sanchez A. Coherent beam combining of ytterbium fiber laser amplifiers. Conference on Lasers and Electro-Optics, 2003.

[17] Ren G, Yi W, Qi Y, et al. US theater and strategic UVA-borne laser weapon. Laser & Optoelectronics, 2016, 11: 17.

[18] Komljenovic T, Helkey R, Coldren L, et al. Sparse aperiodic arrays for optical beam forming and LLDAR. Optics Express, 2017, 25 (3): 2511-2528.