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**ABSTRACT**

Silicon photonics integrated circuits have the advantages of low power consumption, reduced packaging complexity, and high integration density. Nowadays, with the rapid development of autonomous vehicles, the demand for high-resolution optical sensors is growing. The implementation of solid-state light detection and ranging (LIDAR) systems with silicon photonics technology offers the advantages of high resolution, compactness, and high reliability.

In the prior work of our laboratory, a periodic sidewall grating waveguide structure was designed to form an optical antenna, and a 64-channel optical phased array (OPA) is successfully carried out using the silicon photonic process provided by the commercial foundry. After measuring and analyzing of the OPA performance, it is observed that the fabrication error will cause the phase fluctuation of each antenna. The emitted far field pattern from the OPA will have multiple speckles that will severely degrade the beam steering performance.

We develop the optimization scheme to counter the phase errors from the fabrication process. For uniform OPAs, we aim to suppress the side lobes speckles beside the main lobe by exploiting a phase compensation at each antenna. The method of group phase correction proposed in this work can not only significantly reduce the computation time, but also effectively suppress the side lobe energy. In addition, it enhances the performance of the phase control. The peak to side lobe level (PSLL) for uniform 64-antenna OPAs after the phase correction is 16.74 dB and the full width at half maximum (FWHM) is 0.16 degree. Since the grating lobes of the uniform optical phased array are periodic, the steering angle will be limited by the grating lobes. In order to solve this problem, the aperiodic OPAs were designed using the same optimization algorithm. The antennas can be spaced in the range of 2.2 to 6.6 to meet the fabrication limitation on the linewidth and gaps for the antennas patterns. The aperiodic optical phased array can efficiently suppress the grating lobes and broaden the beam steering angle. The optimized PSLL is 12.01 dB at phase shift and 11.89 dB at phase shift. The maximal steering angle is approximately 52.7 degree on one side.

The newly designed OPAs with aperiodic antenna arrangement can not only meet the requirements of semiconductor foundry design rules, but also increase the beam steering range. The design was successfully tapped out for manufacturing.

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**CHAPTER 1 – INTRODUCTION**

* 1. **Introduction**

In recent years, with the rapid advancement of the related applications and technology, the artificial intelligence (AI), 5G communication technology, and internet of things (IOT) have been more and more popular. Due to the demand of processing and transmission of huge amount of data, we need compact transceiver modules with broad network bandwidth and low power consumption. Therefore, the photonic integrated circuit (PIC) has become one of the key technologies to realize the devices and circuits for optical transceivers [1].

The major differences between the electronic integrated circuit and PIC are the transmission signal and material. The latter uses silicon waveguides to propagate optical signals, while the former uses copper wires to propagate electrical signals. Using the electronic integrated circuit to transmit and process signals will consume more power, reduce bandwidth, and increase cost. Comparing to the transmission with copper wires, exploiting light to transmit and process signals can reach much longer transmission distance for the much reduced power loss. The popular choice of silicon PIC is because of its low loss in the optical communication wavelength window, large bandwidth, and compatibility with standard complementary metal-oxide-semiconductor processes [2]. In addition, the use of existing high-end semiconductor manufacturing technology to produce PICs can not only maintain the superior photonic characteristics, but also reduce the costs from rapid mass production.

With the rapid development of autonomous vehicles, the demand for sensor resolution is fast growing. Since silicon is transparent in the optical communication wavelength band, which has better eye safety for using a laser light than the visible wavelength, the PIC based optical radars is often designed to operate in this wavelength range to accurately identify the changes in the surrounding environment of self-driving cars [3][4]. The PIC based solutions will replace the existing technology and become the primary choice for next-generation light detection and ranging (LIDAR) systems.

**1.2 Motivation of this research**

In recent years, with the commercialization of various advanced products, the market for autonomous vehicles has developed rapidly. Furthermore, the demand for sensors and research is on the rise. The sensors on autonomous vehicles are divided into four parts: camera, ultrasonic sensors, radars, LIDARs. Due to their superior resolution, LIDARs are the primary choice for mast car manufacturers to implement Advanced Driver Assistance Systems (ADAS) for self-driving cars [5][6].

LIDAR is one of the key technologies for the autonomous vehicle and expect to have a big market [7]. It offers many advantages such as superior spatial resolution, high computational speed, and high environmental readability [8]. LIDARs are classified into mechanical LIDARs, micro-electromechanical-system (MEMS) LIDARs, and solid-state LIDARs. Comparing the solid-state LiDAR with the other two types of LIDARs, it has small size, low power consumption, and high reliability.

Nowadays, the related research on LIDAR has become very diverse and mature, and the applications of LIDARs can be found in the daily life. The concept of solid-state LIDAR comes from the traditional microwave array antenna. The arrayed waveguide structure is used to realize the optical phase array (OPA) to achieve the beam steering [10].

|  |
| --- |
| Figure 1- 1: Schematic structure of OPA |

Fig. 1-1 shows the schematic structure of a 2xN OPA, where each 1xN OPA consists of an 1xN optical splitter, N optical phase shifters, and N optical antennas. The input light is uniformly distributed to N output waveguides by the optical splitter. Each waveguide is connected to an optical phase shifter for phase control and emit by the optical antenna. The output beam is an interference result of the optical antenna array, so the output beam angle can be steered by adjusting the relative phases among the lights to the optical antennas. Since the optical antenna is made of diffraction gratings, the output beam angle can also be changed by tuning the wavelength of the input light. Therefore, two-dimensional beam steering can be achieved by tuning laser wavelength as well as tuning the phase shifters.

Since it uses a semiconductor process to realize the OPA, the fabrication error will result in phase fluctuation on the light entering each optical antenna. The phase fluctuation causes strong side lobes (or speckles) on the far-field pattern. For LIDAR applications, we have to suppress the side lobes in the far field pattern and maintain the intensity of the main lobe. Therefore, the optimization of OPA phases and correction of phase error for each optical antenna to obtain the optimal far field pattern is the main target of this research. It is possible to realize the optimal phases control by the optimization algorithm [11].

More and more companies and research institutions are investing in the research and development of solid-state LIDARs [12][13]. The applications of LIADRs will not be limited to self-driving cars. They can be applied to medical care, national defense, and aerospace industrials. Currently, there is not much research on developing the PIC based solid-state LIDAR in Taiwan. This research could contribute to the development of the LIDAR technology.

**1.3 Brief overview of OPAs**

The research on LIDAR has become very diverse and mature. The peak to side lobe level (PSLL) is one of the most important parameters in OPA design. Poor PSLL can significantly degrade the system performance and power efficiency of LIDARs. Side lobe reduction is a challenging task in beam forming and beam steering by using OPAs. As the number of optical antennas in an OPA increases, the complexity of control and calibration also becomes very challenging. There are increasing number of related research on this subject in recent years. To suppress the side lobes in an OPA, various schemes are proposed to varying the parameters like the number of antenna elements, steering angle, antenna spacing, and phase correction [14]. Different synthesis techniques, such as genetic algorithm, particle swarm optimization algorithm, and stochastic gradient descent have been successfully used for optimizing the PSLL [15][16]. OPAs are one of the most complex PICs with demonstrations of up to a few thousand of elements. The component counts is likely to be continuously increases in the future. As the complexity increases, the design and control become more challenging. We will make an overview of recent research related to phase correction and OPA optimization as follows.

Uniform OPAs provide advantages in flexibility and versatility. By changing the phase of each element of the array, the far field pattern can be controlled and reconfigured. The output beams can be shaped by shifting the phase of each element to form constructive or destructive interference and by steering the main beam of the array along a chosen direction. Table 1-1 compares the far-field performance of uniform OPAs in recent researches.

|  |  |  |  |
| --- | --- | --- | --- |
| Table 1-1: Comparison of different method of uniform OPA | | | |
|  | P. Harikumar 2011 [17] | T. Komljenovic 2018 [15] | M. Sharifi 2018 [18] |
| number of antenna | 28 | 512 | 8 |
| Optimization method | Fast fourier transform | Deterministic Stochastic Gradient Descent | Adaptive Dispersion Invasive Weed Optimization |
| PSLL (dB) | 17 | 23 | 17.99 |

There exist grating lobes in the far field pattern of uniform OPAs, which results in a small beam steerable range. It has been demonstrated in the literature that the grating lobes can be suppressed by using aperiodic OPAs. By suppressing the grating lobes, the beam steering range can be extended, and the speckles in the far field can also be reduced. Table 1-2 summarize the far-field performance of aperiodic OPAs in recent researches.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Table 1-2: Comparison of different aperiodic OPAs | | | | |
|  | J. C. Hulme 2015 [19] | David N. Hutchison 2016 [20] | M. C. Shin 2020 [14] | He, X., 2021[16] |
| Number of antenna | 32 | 128 | 64 | 1024 |
| Optimization method | Gaussian array | gradient-search algorithm | Genetic algorithm | Particle swarm optimization |
| PSLL (dB) at 0° steering angle | 13.9 | 10 | 17 | 20.5 |
| Maximum steering angle (°) |  | 40 |  | 60 |

OPAs of large PSLL and wide steerable angle can find broad applications in laser communications and LIDAR systems. Some designs can produce good performance, but the parameters may be difficult to implement in practical fabrication. The antenna spacing of the arrayed antenna will affect the performance of the far field. If the spacing is too large, the beam steering range will be limited, which a small spacing may be difficult to meet the fabrication limitation. Our research will consider the fabrication feasibility and the PSLL performance for each steering angle.

**1.4 Organization of dissertation**

The thesis was organized as follows. In Chapter 1 we introduce the applications of LIDARs and optical phase arrays and the motivation of this work. Chapter 2 discusses the basic principles related to the key devices used in this research. Chapter 3 gives a brief description of device structure and characteristics. The design principle is also discussed in this chapter. In Chapter 4, we present our approach and the simulation methodology, which aims to optimize the far field pattern of an OPA. The simulation results and analysis are described in Chapter 5. Finally, Chapter 6 summarizes the results and findings of this thesis.

**CHAPTER 2 – BASIC PRINCIPLE**

The output beam of an OPA is the result of the interference from an array of optical antennas, which direct the light toward the chip surface by using the diffraction theory. Therefore, we will briefly introduce the interference and diffraction theory in this chapter.

**2.1 Interference theory**

In 1678, Huygens completed his work “Traitė de la Lumiere” in 1690 and is now known as “Huygens principle”. During the propagation of a wave, any point on the wavefront can be regarded as a new point wave source. These point wave sources will generate new waves in the direction of the wave, which are spherical waves as shown in Figure 2-1. The result of the superposition of the waveforms of these point wave sources is called the envelope of the wave. It will become the next moment of wavefront. Diffraction and interference are the two major phenomena of wave optics. Huygens principle explains the wave theory, which will help us understand the diffraction and interference phenomena.

|  |
| --- |
|  |
| Figure 2-1: Schematic illustration of Huygens principle [21] |

The interference happens when two or more lights overlap. If the two overlapped lights have the same phase in the propagation or their phase difference is an integer multiple of 2π, the peaks of the two lights will overlap and result in a constructive interference. On the contrary, if the two lights have phase difference of an odd integer multiple of π, i.e., when the wave crest of one light corresponds to the wave trough of the other one, the two lights will have destructive interference.

A famous interference experiment was demonstrated by Young in 1801 with double slits, as showed as Figure 2-2. The two light sources have the same wavelength, so the phase difference between these two lights remains fixed. Stable interference phenomenon can be achieved with coherent sources. The light passes through the two parallel slits S1 and S2 on the screen A to generate a spherical wave centered on the slit. These two spherical waves will overlap in space and form bright and dark interference patterns on screen B, as shown in Figure 2-3.

|  |
| --- |
|  |
| Figure 2-2: Schematic illustration of Young’s double slits [22] |
|  |
| Figure 2-3: Two lights interference |

The distance between the two slits is *d*, and the distance from the slit to the screen is *L*. Assuming that the light propagates in a vacuum, the optical path difference between the two slits is,

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | |  | (2.1) | |
|  |  | | | (2.2) |
|  |  | | | (2.3) |
|  |  | | | (2.4) |

After obtaining the optical path difference between the two slits, the phase difference can be expressed as:

|  |  |  |
| --- | --- | --- |
|  |  | (2.5) |

If the phase difference of two lights is an integer multiple of 2π, it will generate constructive interference. On the contrary, if the phase difference of two lights is an odd integer multiple of π, it will produce destructive interference. That is,

for constructive interference,

|  |  |  |
| --- | --- | --- |
|  |  | (2.6) |

for destructive interference,

|  |  |  |
| --- | --- | --- |
|  |  | (2.7) |

From these formulas, we could obtain the interval between two adjacent bright or dark strips is , as shown in Figure 2-4. Therefore, if the distance *d* between the two slits is changed, the distance between the bright and dark stripes will also be changed.

|  |
| --- |
|  |
| Figure 2-4: Schematic illustration of interference pattern |

**2.2 Diffraction theory**

**2.2.1 Fresnel diffraction**

Fresnel diffraction refers to the diffraction phenomenon in the near field region. This formula can be used to calculate the propagation of lights in the near field.

|  |
| --- |
|  |
| Figure 2-5: Schematic illustration of Fresnel diffraction |

From Figure 2-5, the Sommerfeld formula at a point (x, y) is given by [23],

|  |  |  |
| --- | --- | --- |
|  |  | (2.8) |

where

*E(x’, y’ 0)* is the electric field at the aperture,

|  |  |  |
| --- | --- | --- |
| *r = ,* and |  | (2.9) |

*i* is the imaginary unit.

Firstly, we can simplify the formula by introducing the substitution,

|  |  |  |
| --- | --- | --- |
|  |  | (2.10) |
|  |  | (2.11) |

Next, by the binomial expansion,

|  |  |  |
| --- | --- | --- |
|  |  | (2.12) |

The Fresnel approximation is obtained by assuming that the third term and the higher order terms are very small. Therefore, we can ignore third term and the higher-order term. That is,

|  |  |  |
| --- | --- | --- |
|  | ,  *k* is the wavenumber | (2.13) |
|  |  | (2.14) |

From Fresnel approximation, *r* can be approximated as,

|  |  |  |
| --- | --- | --- |
|  |  | (2.15) |

Substitute *r* back to formula (2.8), the Fresnel diffraction integration formula can be given by (2.16),

|  |  |  |
| --- | --- | --- |
|  |  | (2.16) |

**2.2.2 Fraunhofer diffraction**

Fraunhofer diffraction occurs outside the observation distance of Fresnel diffraction. The Fresnel diffraction integral formula in the form of Fourier transform is used as a far-field approximation to obtain the Fraunhofer diffraction integration formula [23].

|  |  |  |
| --- | --- | --- |
|  |  | (2.17) |
|  |  | (2.18) |

When the screen pattern is much smaller than the distance multiplied by the wavelength, Fraunhofer diffraction approximated is given by,

|  |  |  |
| --- | --- | --- |
|  |  | (2.19) |
|  |  | (2.20) |
|  |  | (2.21) |

Fraunhofer approximates to 1, and substitutes the formula of Fresnel diffraction integration in Fourier transform form,

|  |  |  |
| --- | --- | --- |
|  |  | (2.22) |

This Fraunhofer diffraction formula describes the diffraction phenomenon of light in the far field. The amplitude is inversely proportional to the propagation distance. Besides, the far-field distribution is proportional to the Fourier transform of the input pattern .

**CHAPTER 3 – INGREDIENTS OF OPTICAL PHASED ARRAYs**

In this chapter, the optical components used in the design of optical phased array will be introduced.

**3.1 Multimode interference**

The multimode interference (MMI) is an optical splitter in the photonic integrated circuit, and its structure is shown in Figure 3-1.

|  |
| --- |
|  |
| Figure 3-1: Structure of multimode interference |

The component has the characteristics of broadband, insensitivity to wavelength, arbitrary splitting ratio, and compact size, so it is suitable for constructing LIDARs. The light splitting with the multimode interference is achieved by using a wide waveguide as the coupling area. When the optical signal propagates through the wide waveguide, multiple modes will be excited and interfered in the coupling area. According to the self-image Principle [24], with the interference among modes, the light will periodically generate a single or multiple images along the propagation direction.

The interference result after a given propagation distance is given by

|  |  |  |
| --- | --- | --- |
|  |  | (3.1) |

where *x* is the width direction of MMI, *z* is the propagation direction, is the expansion coefficient of the ith mode, and is the light field distribution of the ith mode. also can be approximately expressed in (3.2) and (3.3) [25],

|  |  |  |
| --- | --- | --- |
|  |  | (3.2) |
|  |  | (3.3) |

is the propagation constant, which can be expressed by Eq. (3.4), where is the refractive index of the waveguide core layer, is the operating wavelength, and is the effective width of the wide waveguide in the multimode interference.

|  |  |  |
| --- | --- | --- |
|  |  | (3.4) |

From the difference and , the beating lengths can be written as:

|  |  |  |
| --- | --- | --- |
|  |  | (3.5) |

The light field after propagation over length *L* can be expressed as:

|  |  |  |
| --- | --- | --- |
|  |  | (3.6) |
|  |  |  |

For an arbitrary input position to the MMI coupler, the length to form *N* images of the input light is given by Eq. (3.7) [25], where *P* is an integer greater than zero. *P* and *N* are integers without common divisors

|  |  |  |
| --- | --- | --- |
|  |  | (3.7) |

If light enters from the center of the coupling area, odd mode will not be excited in the coupling area [25], and the length to form N-images is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3.8) |

If the input light enters from one third of the coupling area, m = 2, 5, 8... modes will not be excited, and the length to form N-images can be obtained from [25]:

|  |  |  |
| --- | --- | --- |
|  |  | (3.9) |

From Eq. (3.7)-(3.9), the MMI length for 1N optical splitter can be determined.

**L]]3.3 Optical antenna**

Figure 3-3 shows the schematic of an optical antenna. The light source entering the periodic grating structure can be emitted perpendicularly to the surface of the wafer. The light fields generated by different grating positions will interfere in the air, and then a concentrated light beam is generated at a certain distance. We can apply this operation to an OPA to collimate and steer the light beam so as to image the surrounding environment.

|  |
| --- |
|  |
| Figure 3-3: Schematic illustration of an optical antenna |

When light enters the periodic grating structure, Bragg diffraction occurs because the light is affected by the periodic change of the effective refractive index of the grating. The diffraction formula can be written as:

|  |  |  |
| --- | --- | --- |
|  |  | (3.12) |

: Effective refractive index of grating

Refractive index of waveguide cladding layer

: The angle of the diffracted light

: Wavelength

: Grating period

From Eq. (3-14), adjusting the wavelengths of the input light will change the emission angle of the beam [28]. This provides the beam control along the light propagation direction, which is called the antenna direction here.

Since the optical antenna is a periodic grating structure, its emitted light is affected by the grating structure. From Fraunhofer diffraction [23], when the intensity of light changes in a sinusoidal function, the light transmission function is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (3.13) |

Fig. 3-4 depicts the light transmission function. If we applied the above function to describe a grating along -direction with finite length and width, is the amplitude of the grating, is the frequency of the grating. is the width of the grating, and is the length of the grating. , where is the grating period. The terms in the first parenthesis stands for the grating function and the other terms are the aperture function.

|  |
| --- |
|  |
| Figure 3-4: Light transmission of sinusoidal function |

The Fourier transformation of the grating function and aperture function can be written as:

|  |  |  |
| --- | --- | --- |
|  |  | (3.14) |
|  |  | (3.15) |

The far-field diffraction of an optical antenna can then be obtained from the convolution of Eqs. (3.14) and (3.15) as:

|  |  |  |
| --- | --- | --- |
|  |  | (3.16) |

where is related to the amplitude of the main beam. The Fraunhofer diffraction pattern can be expressed as:

|  |  |  |
| --- | --- | --- |
|  |  | (3.17) |

The light field distribution of far field diffraction is the superposition of three functions. The intensity peaks occur at *x = 0, x = , x = ,* as shown in Fig. 3-5.

The intensity distribution can be obtained by squaring the field given in Eq. (3.17). Typically, , since the respective peaks are very far apart, the overlapping parts of the main peaks of the three functions and the side lobes of other functions will be omitted. The intensity distribution becomes:

|  |  |  |
| --- | --- | --- |
|  |  | (3.18) |
|  | | |
| Figure 3-5: Normalized far field distribution [21] | | |

When the aperture () is larger, which means the antenna length is longer, the Full Width at Half Maximum (FWHM) of main lobe will be smaller. The smaller width of the main lobe means a narrower optical beam and a higher angular resolution in using the optical antenna for optical sensing. That is, a longer optical antenna will provide a higher angular resolution for beam steering. On the other hand, the beam divergence along the y-direction (array direction for an OPA) is usually large due to the small grating width to layout the optical antenna array. However, the interference from multiple antennas can still achieve small divergent angle along this direction.

**3.4 Optical phased array**

When an array of optical antennas are properly arranged to construct an optical phased array, the emitted light from the adjacent antennas will interfere with each other. This is similar to a multi-slit interference phenomenon. If the phase of each antenna in the antenna array is the same or an integer multiple of 2, the emitted light will be constructively superimposed to form a narrow beam along the array direction.

Referring to the geometry of Figure 3-6, we assume that all the elements have identical amplitudes. Besides, each succeeding element has a progressive phase relative to the previous one. According to the principle of interference, the phase difference between adjacent antennas can be expressed as:

|  |  |  |
| --- | --- | --- |
|  |  | (3.19) |

where

is the phase difference of adjacent antennas

is the optical path difference

is the operation wavelength

is the wavenumber

is the pitch of each antenna

is the beam divergence angle in array direction

|  |
| --- |
|  |
| Figure 3-6: Schematic illustration of interference of optical phased array [21] |

An antenna array with identical elements of the same spacing and a progressive phase is known as a uniform array. The array factor can be obtained by considering the elements to be point sources. The array factor is given by [21]:

|  |  |  |
| --- | --- | --- |
|  |  | (3.20) |
|  |  | (3.21) |

This equation can be rewritten as,

|  |  |  |
| --- | --- | --- |
|  |  | (3.22) |

where

|  |  |  |
| --- | --- | --- |
|  |  | (3.23) |

Since the total array factor of the uniform array is a summation of exponentials, it can be represented by the vector sum of unit amplitude and N phasors relative to the previous phase , as shown in Figure 3-7. It is apparent from the phasors diagram that by properly selecting the relative phase between the elements, the amplitude and phase of array factor can be controlled in a uniform array. Furthermore, in non-uniform arrays, the amplitude as well as the phase can be used to control the formation and distribution of the total array factor. By adjusting different phase differences, the optical antenna array can generate different beam divergence angles to achieve the effect of beam steering in the array direction.

|  |
| --- |
|  |
| Figure 3-7: Schematic illustration of phasor diagram [21] |

Eq. (3.22) can also be written as,

|  |  |  |
| --- | --- | --- |
|  |  | (3.24) |

If the reference point is the physical center of the array, the array factor of Eq. (3.24) reduces to,

|  |  |  |
| --- | --- | --- |
|  |  | (3.25) |

To normalize the array factors so that the maximum value is equal to unity, the normalized form is given by,

|  |  |  |
| --- | --- | --- |
|  |  | (3.26) |

The far field of the optical antenna array is formed by the interference of the far field distribution of all optical antennas. If a single optical antenna is regarded as a slit, the optical antenna array interference is regarded as multi-slit interference. Therefore, the multi-slit interference and diffraction theory can be used to explain the far field distribution of the optical phased array as shown in Figure 3-8.

|  |
| --- |
|  |
| Figure 3-8: Schematic diagram of far field of an optical phase array |

From the results of interference theory and diffraction theory that the size of the optical phased array () will affect the divergence angle of the main beam in the array direction. Here we treat as the total width of the antenna array not of a single antenna. A larger antenna array will form a smaller divergence angle of the main beam. For the phased arrays with the same number of antennas, the smaller optical antenna spacing contributes more to the main beam. Therefore, the side lobes of the beam are smaller, and the side lobes appear farther from the main beam. In summary, a smaller antenna spacing and a larger number of antennas have better steering range and scanning resolution for optical phased arrays.

From the relation of beam steering and the phases compensation, the maximum beam steerable angle is limited by the two grating lobes on both sides of the main lobe. When we apply phase shift to the optical phased array, the beam will steer to the maximum angle. From Eq. (3.22), when the beam steers to a given angle, the phase compensated by each antenna presents a multiplication ratio. Because each antenna has equal pitch spacing in a uniform optical phased array, the phase shift of the antennas will be an arithmetic sequence as shown in Figure 3-9.

|  |
| --- |
| Figure 3-9: The relation with phases and each antenna when steering |

**CHAPTER 4 – SIMULATION METHOD**

**4.1 Optimization algorithm**

**4.1.1 Genetic algorithm**

Genetic algorithm (GA) is a search algorithm used to solve the optimization problems and is a kind of evolutionary algorithm [15][29]. The theory of genetic algorithm is based on the concept of evolution and elimination of “natural selection or survival of the fittest” developed by Darwin's **“**On the Origin of Species**”** in 1859. All species are under the test of the natural environment. Those with strong adaptability gradually survive, while the poorly adaptability are gradually eliminated. Genetic algorithms were originally developed based on some phenomena in evolutionary biology, including initialization, natural selection, crossover, and mutation [30][31][32]. We will adopt this method for the phase optimization of OPAs.

The array factor discussed in Chapter 3 will be used for phase optimization of OPAs. Since at least 64 antennas is used in an OPA, the optimization involves a great deal of variables and requires a very efficient algorithm. The objective function for the optimization of OPA is often set to minimize side lobes in the far-field pattern. Since the objective function is not convex [33], there may be a large number of local minima that cannot be distinguished from the global minimum. The calculation of all the minimal points becomes impractical and very time-consuming as the number of antenna elements in the OPA increases.

There are many kinds of phase permutations and combinations that can lead to similar far field patterns, it is hard to find the unique phase combination that produce the best far-field pattern. Therefore, our target is to find the phase combination to make the far field pattern to have satisfactory radiation patterns.

|  |
| --- |
| Figure 4-1 Schematic illustration of genetic algorithm |

Figure 4-1 is the schematic illustration of the genetic algorithm. For the initialization, we have to generate 100 initial individuals to be a population. First of all, each of the initialized individuals generates 64 random phases in the range of to . These will be the input to the optimization algorithm. After that, it will start the fitness calculation.

For the selection, the target is selecting the best individuals in the current generation as parents for producing the offspring of the next generation. Based on the calculation result of the fitness function, we could decide to keep the number of parents. Each individual in the population will be ranked from high to low according to the result of the fitness calculation. The first 50 individuals will be designated as the parents of the next generation.

For the crossover, we first decide the point at which crossover takes place between two parents. If we set a point at the center as shown in Figure 4-2, the first 32 chromosomes of one parent and the last 32 chromosomes of the other will form the next offspring because each individual has 64 chromosomes. If we set two points as shown in Figure 4-3, the total gene of each parent will be cut into three segments. In addition, we set the position of the crossover point to be generated by random numbers, that is to say, there are 63 choices for the crossover point. Finally, a total of 100 children will be generated.

For the mutation, there is a certain probability of mutation in the offspring. In this part, we can not only set the chromosomes that mutations will happen, but also set the probability of mutation rate. An individual has a quarter of chromosomes that may have mutations. Besides, the mutation rate of each chromosome is between 10% and 90%. Figure 4-4 is the schematic illustration of mutation. If the mutation rate of the chromosome reaches a certain standard, the individual's final gene sequence is not entirely from the parents but with some mutations.

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| --- |
|  |
| Figure 4-2: Schematic illustration of one point crossover |
|  |
| Figure 4-3: Schematic illustration of two points crossover |

Figure 4-4: The schematic illustration of mutation

After many iterations, the offspring of the last generation will be output as the final result. We set the number of iteration to one thousand times, and the best individual of the population in the thousandth time will be the result of optimization.

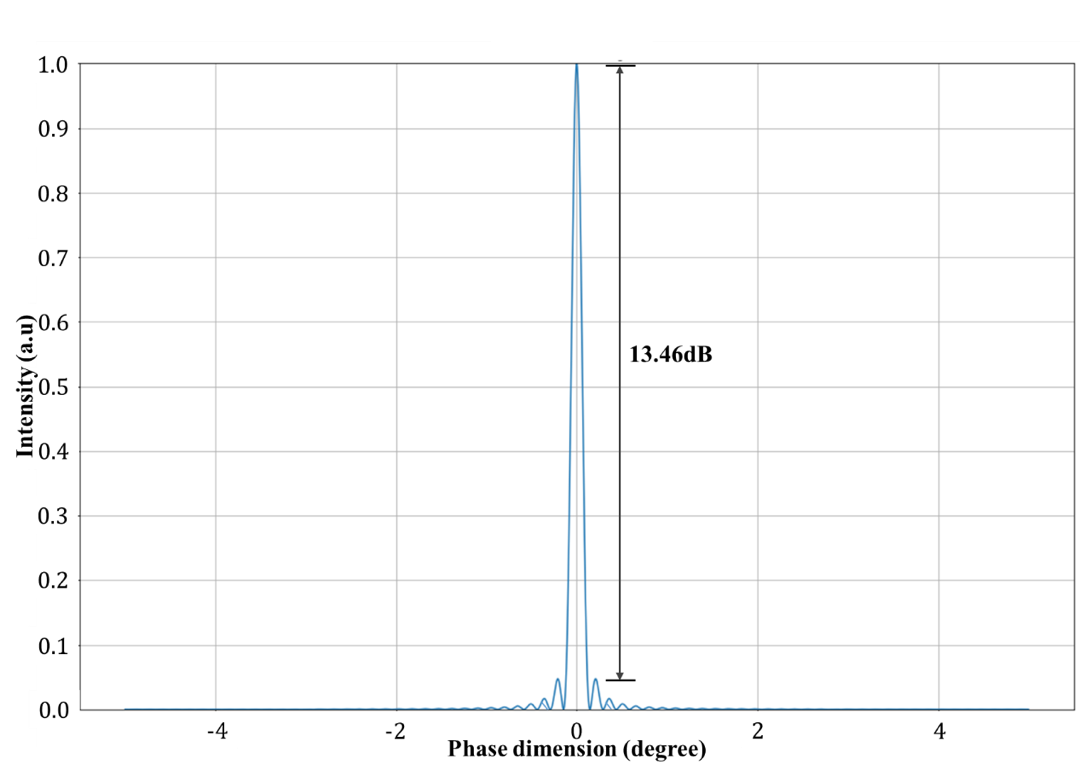
**4.1.2 Fitness function**

The higher the fitness level of an individual, the better are its features. Therefore, it has a higher chance of reproduction. There are two requirements for the fitness function. One is the distribution of the total intensity of the far field pattern, and the other one is the value of the Peak to Side Lobe Level (PSLL) [34]. PSLL is defined as the maximum value over the minor maximum value of the array factor. The general form of fitness function is given by,

|  |  |  |
| --- | --- | --- |
|  |  | (4.1) |
|  |  | (4.2) |

From Eq. (3.28), we can obtain the normalized far field pattern as shown in Figure 4-5. Table 4-1 provides the parameters for this uniform optical phase array. By calculating the area of the whole far field pattern, the total intensity of this far field can be obtained. If the intensity of the far field is more concentrated in the main lobe, the far field pattern is optimized. The smaller an individual’s far field area is, the higher fitness level will be obtained.

|  |  |  |  |
| --- | --- | --- | --- |
| Table 4-1: Parameters of uniform optical phase array | | | |
|  | Number of antenna | Pitch spacing () | Operating wavelength (nm) |
| Uniform OPA | 64 | 9.5 | 1550 |

The other requirement to evaluate the fitness is the Peak to Side Lobe Level (PSLL). If the value of PSLL is greater, it means that the ratio of the main lobe to the max side lobe is higher. Thus the maximum of the first minor lobe of the array factor of Eq. (3.28) is 13.46 dB down from the maximum at the main lobe, as shown in Figure 4-6. Therefore, the higher PSLL indicates a better individual’s fitness.

|  |
| --- |
| Figure 4-5 Normalized far-field pattern |

|  |
| --- |
| Figure 4-6: PSLL of normalized far-field pattern |

In summary, if the initialized individual meets the standard of above two conditions with this optimization algorithm, it means a higher fitness level and will be ranked former. Therefore, these individuals will become parents, and then generate the next offspring. In the next section, we will introduce how to apply this optimization algorithm to the uniform optical phased array and aperiodic optical phase array.

**4.2 Far field correction of uniform OPAs**

**4.2.1 Group correction**

Because of the fabrication induced fluctuation in the waveguide geometry and composition for the OPA devices, there will be a phase error associated with each waveguide when the light propagates [35]. In the far field pattern, there will be some small side lobes near the main lobe due to the phase errors. In order to solve this problem to suppress the side lobes, we came up with a method to add a certain voltage for each antenna and compensate the phase. Heating the waveguide to change the effective refractive index of the waveguide under a phase shifter will change the phase difference of each antenna. Then the far field pattern can be optimized to obtain the maximum PSLL result. Since there are at least 64 phase shifters in an OPA, it is a very complicated task for the phase compensation without an efficient optimization scheme.

Our design of uniform optical phased array [10] uses 64 optical phase shifters and 64 optical antennas of the pitch spacing of 9.5 , which was limited by the design rules of the semiconductor foundry. The operating wavelength is 1550 nm. Figure 4-7 is the schematic illustration of uniform optical phased array. After the interference and diffraction, the first grating lobes locate at 9.66 degrees relative to the main lobe, as shown in Figure 4-8. If we want to obtain more accurate results, we have to increase the resolution of phase in the optimization. The compensation phase of each antenna is between 0 and 2 with a step size of . This requires a great effort in optimizing an optical phased array with 64 antennas. To reduce the computing time, we develop a group phase correction scheme to solve this problem. Figure 4-9 is the flow chart for the phase correction.

|  |
| --- |
| Figure 4-7: Schematic illustration of uniform optical phased array |
| Figure 4-8 Far field distribution of the designed uniform optical phased array | |

The simulation can be divided into eight steps:

Step 1: For each antenna in the ideal case, a phase of 0 to 2 is randomly assigned to simulate an optical phased array with potential phase errors.

Step 2: We will first steer the far field beam to the required angle, and then start the correction step. From Eqs. (3.24) and (3.25), the value of item is changed to perform the beam steering. For the uniform optical phased array, by steering the far field beam angle from a small angle to a large angle, this item will also increase in arithmetic sequence. By finding the appropriate value of , we can fix the far field beam at the designated angle and then start the phase correction.

Step 3: The 64 antennas are divided into two groups of 32 antennas. Firstly, we fix the phase of one group, then adjust the phase on the other group. The phase is adjusted until a relatively large PSLL of the far field pattern is obtained. Then, we fix the phase of this group and adjust the phase to the other group to find a relatively large PSLL again. During the optimization process, the phase compensation is the same to all antennas in one group.

|  |
| --- |
|  |
|  |
| Figure 4-9: Flow chart for optimizing a uniform optical phased array |

Step 4: We keep the compensation phase of each antenna in the previous step, and divided each group into two subgroups. Therefore, each subgroup has 16 antennas. We start the phase correction from the center subgroups as shown in Figure 4-10. After obtaining the relatively large PSLL, the phase is fixed for this subgroup. Repeat the same steps to perform phase compensation for the other three subgroups until a relatively large PSLL in the far-field pattern is obtained.

|  |
| --- |
| Figure 4-10: Step of phase correction |

Step 5 ~ Step 7: Repeat the method of the third and fourth steps by dividing the antenna array into more subgroups. More accurate correction is expected when this procedure proceeds further. With this method, the calculation time and steps required for phase correction are much less than that of optimizing the phase of all antenna at one time.

Step 8: After the above steps, we can obtain an optimized far-field pattern by applying the genetic algorithm introduced in the previous sections for further phase correction. The initial population is the result after Step 7, that is, each individual has a total of 62 chromosomes. Base on the phase corrections from Step 3 to Step 7, the far field pattern has been nearly optimized. In this step, the phase compensation range in the genetic algorithm is set from to . If the individual reaches the two conditions mentioned in section 4.1.2 of the fitness function, it will have the opportunity to be the parent who generates the next offspring. Finally, after 1,000 iterations, the final result will be produced.

**4.3 Far field correction of aperiodic OPA**

For the optimization of a uniformly spaced optical phased array, the main target is to suppress the small side lobes which are generated near the main lobe. For the uniformly spaced optical phase array, the side lobes in far field pattern will be periodic. In our first-version optical phased array design, each antenna is arranged at a pitch of 9.5 and the operating wavelength is 1550 nm. There will be a grating lobe for every 9.66 degrees relative to the main lobe. When the LIDAR scans the environment, a strong main beam is needed but the side lobes and grating lobes have to be suppressed. The aperiodic spaced optical phased array was proposed to suppress the grating lobes [19]. It is more feasible method to achieve a large range of steering angle.

For proof of concept, our new optical phased array is designed with 32 antennas. As mentioned in the previous chapter, the closer the pitch spacing of optical antenna is, the farther the grating lobes will be from the main lobe. Due to the limitation on the antenna space by the chip manufacturers, the minimum antenna pitch is set as 2.2 . Thus, the antennas can be spaced in the range of 4.4. The layout of an aperiodic spaced optical phased array is shown in Figure 4-11. The optimization algorithm for the aperiodic OPAs is similar to the procedures stated in the previous section, but the antenna spacing rather than the antenna phase is optimized to obtain the optimal far-field pattern.

|  |
| --- |
| Figure 4-11: Schematic illustration of aperiodic optical phased array |

For the initialized population of optimization algorithm, there are total 50 individuals. Because the optical phased array of 32 antennas has 31 intervals, each individual has 31 chromosomes and the range of the pitch in each individual is 2.2 to 6.6 . Our purpose is to maximize the PSLL for all possible steering angles.

**CHAPTER 5 – SIMULATION RESULTS AND ANALYSIS**

**5.1 Far field pattern of a uniform OPA**

**5.1.1 64-antennas results and analysis**

As mention in the previous chapter, the fabrication error results in a phase error when the light propagates through the optical waveguide in an OPA [17][36]. The phase error for the light to reach each antenna is not the same, so the far-field pattern of the OPA will deviate from its ideal state. As a result, the main lobe he far-field pattern degrades with increasing side lobes. Phase correction by adjusting the phase of the optical phase shifter before each antenna needs to be carried out to suppress the side lobes as well as to increase the main lobe. Figure 5-1 depicts the simulation flow chart for phase correction.

|  |
| --- |
| Figure 5-1: Simulation flow chart for phase correction |

Firstly, we will generate a far field pattern with random phase errors to be the input data for the simulation. The far-field pattern with the phase errors is shown as Figure 5-2. In fact, there are many phase combinations that can make up the same pattern. We then apply phase compensation to suppress the side lobes. The PSLL of the input far field distribution is 1.02 dB. The optical phased array has 64 optical antennas of 9.5 pitch spacing. The operating wavelength is 1550 nm. With phase errors, the main lobe may be indistinguishable and may not appear at the designated angle, which is assumed to be 0 degree in Fig. 5-2.

For a uniform optical phased array, the grating lobes of the far-field pattern will appear periodically [18]. The first grating lobes will appear at 9.66 degrees in our design, so the steerable range with a single main beam is 9.66 degrees. Therefore, the simulation will cover the field of view of 5 degrees. Therefore, the pattern for the other angle range is simply the duplication of the simulated pattern.

|  |
| --- |
| Figure 5-2: Far field distribution with potential phase errors |

After obtaining the input far field distribution with random phase errors, the optimization (or phase correction) procedure is applied to suppress the side lobes. We adopt the group correction scheme mentioned in chapter 4. Firstly, we fix the beam angle at 0 degrees and divide the 64 antennas into 2 groups of 32 antennas. The phase correction ranges from 0 to 2 with a step of 0.01 degree. Figure 5-3 shows the schematic of dividing the optical phased array into two groups. The far field distribution result after optimizing the phases for these two groups is shown as Figure 5-4 (a). As shown in Figure 5-4 (b), the phases of 46.65 and 3.22 degrees are applied to the optical antennas in the left group (Group 1) and right group (Group 2), respectively.

|  |
| --- |
| Figure 5-3: Phases of Group-1 and Group-2 antennas |

|  |
| --- |
| 1. (b)   Figure 5-4: (a) Far field pattern after 1st-stage phase correction (b) Compensated phases for the two groups |
|  |

After phase correction for the first stage, Group 1 and 2, we can find that the side lobes near the main lobe are greatly reduced. Therefore, most of the energy has been concentrated in the main lobe. The value of PSLL has improved from 1.02 dB to 10.98 dB. We then apply the same procedure to the second-stage phase correction by dividing each group of optical antennas into two subgroups, resulting in 4 subgroups in total. That is, before the phase compensation started, the compensated phase for the first two subgroups is 46.65 degrees, and the other two subgroups have the same phase compensation of 3.22 degrees. Using the current phases of each poo0oll,llsubgroup as the initial condition, the optimization procedure is conducted to search for the best compensation phase in each subgroup so that the value of PSLL can be maximized. The schematic of grouping for the 2nd stage is shown in Figure 5-4. The same optimization procedure can be extended to the following stages by further dividing each subgroup to smaller subgroups. The far field pattern after the phase correction of Stage 2 to 5 are shown as Figure 5-6 (a) to 5-9 (a), respectively, with the corresponding phase compensation shown in Figure 5-6 (b) to 5-9 (b).

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| --- |
| Figure 5-5: Schematic illustration of grouping for Stage 2 |

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| --- |
|  |
|  |
| (a) (b)  Figure 5-6: (a) Far field pattern after the 2nd-stage phase correction (b) Compensated phases for the subgroups |
|  |
| (a) (b)  Figure 5-7: (a) Far field pattern after the 3rd-stage phase correction (b) Compensated phases for the subgroups |
|  |
| (a) (b)  Figure 5-8: (a) Far field pattern after the 4th-stage phase correction (b) Compensated phases for the subgroups |
|  |
| (a) (b)  Figure 5-9: (a) Far field pattern after the 5th-stage phase correction (b) Compensated phases for the subgroups |

After performing the phase correction up to Stage 5, where the 64-antennas are divided into 32 subgroups, really good far-field pattern and PSLL value can be obtained. As mentioned in chapter 4, after the group correction is completed, the resultant phases will be the input data into the genetic algorithm. There are two conditions we set for the fitness function: one is the total intensity of the far-field pattern, and the other one is the value of PSLL. The phase compensation range in the genetic algorithm is from to . There are total 62 parts from Stage 1 to Stage 5. In the genetic algorithm, we apply this 62 part as the initialize chromosomes for further phase correction.

The mutation rate of each chromosome is different, ranging from 10% to 90%. Each mutation will increase the phase compensation of the antenna by 5 degrees to 10 degrees. Therefore, the phase compensation of each antenna obtained by the genetic algorithm may be 60 degrees or more than the phase correction result after Stage 5. The far field distribution result after GA optimization is shows as Figure 5-10, and the phase compensation of each antenna is shown as Figure 5-11. The PSLL of final result is 16.74 dB, which is greater than that of ideal uniform OPA without any phase adjustment. It was pointed out in the literature [33] that the PSLL can exceed the ideal case with phase synthesis. That is, adding a set of phases to the optical antenna array may help to suppress the side lobes.

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| --- |
| Figure 5-10: Optimized far-field distribution after applying GA |
| Figure 5-11: Phase compensation for each antenna after applying GA |

The phase correction steps are executed in a sequence. As long as the PSLL criterion is reached in one group phase correction stage, the program will go to the next stage. The PSLL criterion for each stage is set by ourselves. When the group phase correction is finished, the GA optimization step will be executed. Figure 5-12 shows the PSLL value after each iteration. Table 5-1 summarized the corrected PSLL results and the antenna parameters.

|  |
| --- |
| Figure 5-12: PSLL after phase correction |

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Table 5-1: PSLL after each stage and related parameters | | | | | | |
| Stage | 1 | 2 | 3 | 4 | 5 | GA |
| PSLL (dB) | 10.98 | 11.69 | 12.62 | 14.50 | 15.48 | 16.74 |
| Number of antennas: 64  Pitch: 9.5, Wavelength: 1550nm | | | | | | |

In summary, we verify in this section that the group phase correction scheme can work well for phase correction of OPAs. This scheme is much simpler than the optimization without grouping. It is especially beneficial for the applications that require fast and real-time phase correction or optimization. After phase correction with the grouping scheme, the PSLL can be >15dB without using GA optimization. The value of PSLL after the group phase correction can be higher than the ideal case. The beam width (FWHM) of the far field pattern along the array direction can reach 0.16° for a 64-antenna array.

**5.1.2 Beam steering of 64-antenna OPA**

As mentioned in the previous section, the grating lobes will appear in a cycle of 9.66 degree for the antenna pitch used in our OPA design. If the phase difference for each antenna varies from - to , the beam angle of main lobe will be steered from 9.66 degrees to -9.66 degrees [37][38]. Every additional can make the main beam steer for 1 degree.

We can apply similar procedures for the phase compensation of OPAs in the last section to the cases when the OPA is steered to a given angle. Figure 5-13 shows the result of the far-field patterns for the main lobe steering from 4 degrees to 4 degrees. The optical phased array is arranged to have uniformly spaced optical antennas. It is found in the simulation that, after the phase correction is done for 0-degree angle, the same phase compensation can be applied to each steering beam angle and obtain nearly the same value of PSLL (16.74 dB) as the 0 degrees. Again, the PSLL value with the phase correction is better than the ideal case. The phase distribution with and without phase compensation correction are shown as Figure 5-14(a)~(d) for the steering angle of 1 to 4o.

|  |
| --- |
| Figure 5-13: Far-field pattern for steering the uniform OPA with 64 antennas |

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|  |
| Figure 5-14: The phase distribution for the steering angle of (a) 1°(b) 2°(c) 3°(d)4° |

**5.2 Optimization of Aperiodic OPA**

**5.2.1 32-antennas result and analysis**

For the uniform phased array, the range of steering angle of the main beam is by the grating side lobes, which are determined by the antenna pitch (or antenna spacing). There will be no grating side lobes if the antenna pitch is smaller or equal to half the wavelength. However, the half-wavelength pitch is hard to achieve with the PIC technique at the telecommunication wavelengths. The antenna pitch is typically on the order of several m to tens of m due to the limitation on the line width and gap by the semiconductor foundries. On the contrary, for the aperiodic phased arrays, grating lobes on the far-field pattern can be suppressed after the interference and diffraction of the array antennas [39]. This may extend the field of view for the OPA to 90 degrees.

For proof of concept, our new optical phased array is designed with 32 optical antennas. The minimum fabrication process limitation of antenna pitch is 2.2 . Thus, the antenna spacing within 4.4 is used to optimize the aperiodic optical phased array. The closer the pitch spacing between the antennas is, the farther the side lobe will be from the main lobe. Figure 5-15 is the simulation flow chart for the aperiodic OPA.

|  |
| --- |
| Figure 5-15: Simulation flow chart of the aperiodic OPA |

We first fix the main beam angle at 0 degree and start the genetic algorithm. Not like the group correction of the uniform optical phased array, the optimization of aperiodic optical phased arrays is performed to obtain the optimal spacings for the 32 antennas at the same time. First of all, there are 100 initialized populations and each population has 31 chromosomes. In order to meet the limitations of the fabrication process, the range of each chromosome is between 2.2 um and 6.6 um.

Next step is the calculation of the fitness function. It must meet two conditions: one is the lower distribution of the total intensity of the far field pattern and the other is the largest value of PSLL as mentioned in chapter 4. The first 50 individuals will be designated as the parents of the next generation. For the crossover, each has a 50% probability to determine the crossover point to be one or two points. The position of the crossover points are generated by random numbers. Each of the iteration offspring has 100 individuals. There is a certain probability of mutation during each iteration. A quarter of a person's chromosomes may have mutations. That is, there are 16 chromosomes that may have mutations, and these 16 chromosomes are generated by random numbers from 1 to 64. In addition, the mutation rate of each chromosome is between 10% and 90%.

After execution of the optimized algorithm, we will obtain the optimal solution of antenna spacings across the OPA. By applying the solution of antenna spacings to the aperiodic optical phased array, we will obtain the far field patterns with suppressed grating lobes. Figure 5-16 compares the far field patterns for the periodic and aperiodic OPAs. No grating lobes can be observed for the aperiodic OPA, while the PSLL is 10.4 dB and the FWHM is 0.65 degree. It is expected that the PSLL can be enhanced and smaller FWHM can be obtained for the aperiodic OPAs with more optical antennas. Table 5-2 compares the design parameters and results between the uniform and aperiodic OPAs.

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| Figure 5-16: Far-field distribution of uniform and aperiodic optical phased arrays |

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| --- | --- | --- | --- | --- | --- |
| Table 5-2: Comparison of design parameters and results between uniform and aperiodic OPAs. | | | | | |
|  | # of antennas | Wavelength (nm) | Pitch spacing () | PSLL (dB) | FWHM (°) |
| Uniform OPA | 32 | 1550 | 4.4 | 13.46 | 0.6 |
| Aperiodic OPA | 32 | 1550 | 2.2~6.6 | 10.40 | 0.65 |

**5.2.2 Beam steering of 32-antenna OPAs**

In this section, we will introduce the simulation results of beam steering of aperiodic optical phased array. In the previous section, we fix the steering angle at 0 degree. After the pitch distribution result is obtained, we apply the phase difference of the adjacent antennas from 0 to . The result is shown in Figure 5-17, where the PSLL is 9.08 dB when the phase difference is 0 and 6.02 dB when the phase difference is . Because the optical phased array is not uniformly spaced, the far field distribution is different at each beam steering angle. However, the grating lobes are suppressed, so the maximal steering angle can reach 50.6 degrees.

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| Figure 5-17: Beam steering of aperiodic phased array |

In order to solve the problem of degrading PSLL in steering the angle of main beam for an aperiodic OPA, the simulation steps need to be modified. As shown in Figure 5-18, the fitness function needs to be optimized for each steering angle.

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| Figure 5-18: Simulation flow chart of the aperiodic pitch spacing |

Firstly, we generate 50 initialized populations, and each individual has 31 chromosomes. If the individuals meet the criterion of the fitness function, they will be the parents in next generation. After 1000 iterations, we will obtain the final result. As shown in the Figure 5-19, we successfully suppress the side lobes to a relative low level. Therefore, the PSLL at large steering angle could maintain at a reasonably good value. The PSLL is 9.4 dB for phase shift and 9.38 dB for phase shift. The maximal steering angle is 51.8 degree. Figure 5-20 is the optimized 31 antenna spacings. The optimized spacing lies in the range of 2.2 to 6.6 .

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| Figure 5-19: Beam Steering of aperiodic phased array |
| Figure 5-20: Pitch distribution of aperiodic phased array |

After obtaining the result of the optimized aperiodic optical phased array that has a relative higher PSLL at each steering angle, we exploit the group phase correction which was mentioned in previous section to this design. We mainly focus on optimize for the phase shift that corresponds to the maximal steering angle. We divide the phase correction steps into 4 groups, which is divided into 16 parts at the last step that each part has 2 antennas. After the phase correction, the value of PSLL at phase shift is increased to 9.73 dB. Although the improvements on PSLL is not significant, this method can work for aperiodic optical phased array. The PSLL is 9.3 dB when turning the main beam from phase shift to 0 phase shift, slightly lower than the value before phase correction.

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| Figure 5-21: Beam Steering with Phase Correction |  |

**5.2.3 Result and analysis of 64 and 128 antennas**

For the aperiodic phased array, we try to simulate a 64 antennas aperiodic phased array by using a symmetric pitch arrangement. Since there are 63 pitches of 64 antennas optical phased array, the center pitch has to be arranged. The optimization can be conducted for half of the antenna spacings (31) and then the other half of the antenna array is simply the image of the optimized half array. In order to meet the limitation of the fabrication, we first optimize the center pitch within 2.2 μm and 6.6 μm. Figure 5-22 shows the far field distribution of 64 antennas optical phased array with a PSLL of 10.26 dB. The pitch distribution is shown as Figure 5-22, where the center pitch is set as 4.3 μm. Therefore, with the symmetrical and self-imaged antenna pitch arrangement, optimization for fewer parameters of antenna spacing can reduce the computation complexity and save the computing time. In addition, the PSLL result can also be improved.

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| Figure 5-22: 64 antennas aperiodic phased array |
| Figure 5-23: Pitch distribution of aperiodic 64-antenna OPAs |

In order to verify the method of symmetric pitch arrangement, we also apply it to simulate a 128-antennas case with center symmetry. To evaluate whether it works, we simulate the optimized pitch spacing for 64 antennas and 128 antennas cases as the control group.

With the optimized pitch spacing for 64-antenna aperiodic optical phased array, the PSLL is 10.6 dB. Figure 5-24 shows the far field pattern and the pitch distribution. The PSLL performance of 32-to-64 imaged OPA case is slightly lower than the optimized 64 antennas aperiodic optical phased array. However, the computing time of the 64-antennas case is 10 times larger than that of 32-to-64 imaged antennas.

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| Figure 5-24: 64-antenna aperiodic phased array for (a)far field distribution and (b)pitch distribution |

Next, the number of antennas is increased to 128. We simulate three cases: 32-to-128 imaged antennas, 64-to-128 imaged antennas, and optimized 128 antennas. The PSLL is 10.56 dB for the first case, 12.01 dB for the second case, and 12.72 dB for the last one. The far field distribution and the pitch distribution of these three cases are shown in Figure 5-25.

The method of symmetrical pitch arrangement can effectively decrease the computing time and maintain the performance of an aperiodic phased array. The PSLL value of the method is even better than that of the optimized pitch arrangement for the whole antenna array. Table 5-3 compares the computing time of the optimized aperiodic optical phased array with 1000 iterations. The type of CPU is Intel(R) Core(TM) i5-4460. Exploiting the 64-to-128 antennas imaging scheme can save at least half of the computation time than the optimization for the whole 128 antennas.

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| Figure 5-25: 32 symmetric to 128 antennas aperiodic phased array for (a)far field distribution and (b)pitch distribution, 64 symmetric to 128 antennas aperiodic phased array for (c)far field distribution and (d)pitch distribution, 128-antenna aperiodic phased array for (e)far field distribution and (f)pitch distribution |

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| Table 5-3: Computing time of the optimized aperiodic optical phased array | | | |
| Number of antennas | 32 | 64 | 128 |
| Computing time (min.) | 20~30 | 120~150 | 280~320 |

**5.2.4 Beam steering of 64-antenna OPAs**

In order to see the difference between the aperiodic optical phased arrays with 32-to-64 imaged antennas and with the original 32 antennas, we apply phase shift to the optical phase arrays to achieve the maximal steering angle. From Figure 5-26, the PSLL is 10.12 dB at the phase shift. Besides, the steering angle for phase shift is 52.11 degrees, which is slightly larger than the 32-antenna aperiodic optical phased array.

Figure 5-27 shows the beam steering of aperiodic OPAs with 32-to-128 imaged antennas and the phase distribution for the maximal steering angle. After applying π phase shift to the optical phased array, the maximal steering angle is 51.48 degree with a PSLL of 10.03 dB. Figure 5-28 shows the beam steering of OPAs with 64-to-128 imaged antennas and the phase distribution for the maximal steering angle. The maximal steering angle can reach 52.7 degrees with a PSLL of 11.89 dB. Table 5-4 compares the results of the above cases for aperiodic optical phased arrays.

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| Table 5-4: Comparison of different cases of symmetrical optical phased array | | | |
|  | 32 symmetric to 64 antennas | 32 symmetric to 128 antennas | 64 symmetric to 128 antennas |
| PSLL (dB) | 10.12 | 10.03 | 11.89 |
| Max steering angle (°) | 52.11 | 51.48 | 52.7 |

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| Figure 5-26: Beam Steering of aperiodic OPA with 32-to-64 imaged antennas |
| Figure 5-27: Aperiodic OPA with 32-to-128 imaged antennas (a) beam steering and (b) phase distribution for the maximal steering angle |
| Figure 5-28: Aperiodic OPA of 64-to-128 imaged antennas (a) beam steering and (b) phase distribution for the maximal steering angle |

**CHAPTER 6 – CONCLUSIONS AND FUTURE WORK**

**6.1 Conclusions**

In the prior research of our laboratory, a periodic sidewall grating structure waveguide was designed to realize an optical antenna with uniform emission pattern. The optical phased arrays of 64 optical antennas is successfully fabricated using the silicon photonic process provided by a commercial semiconductor foundry. After measuring and analyzing of the OPA performance, it is observed that the fabrication fluctuation in the optical waveguide geometry will cause phase errors to the OPA and degrade the output beam quality. Optical speckles appear in the far-field pattern, and an effective scheme to correct the phase errors is needed to suppress the optical speckles. In this work, we exploit a GA optimization algorithm to suppress the side lobes in the far-field pattern for uniform optical phased arrays. We also design a new optical phased array with aperiodic antenna spacing that could eliminate the grating lobes and extend the steering angle. The major contributions are summarized as follows:

The phase error of each antenna prevents the main beam from being concentrated in the far field pattern and severely degrades the beam steering performance. We develop a novel group phase correction scheme to counter the phase errors from the fabrication process. With the group phase correction scheme and GA optimization algorithm, we can obtain really good PSLL for the uniform optical phased array. It can not only suppress the side lobes near the main lobe, but also concentrate the energy to the main beam. This method makes it possible to significantly reduce the computation time. The optimization procedures is especially for the phase correction in experimental practices. The PSLL of the uniform optical phased array after group phase correction can achieve 16.74 dB. Besides, the full width at half maximum (FWHM) of the main beam is 0.16 degree.

Because the designed uniform optical phased array has an antenna spacing of about 10 μm, the grating lobes will appear every 9.66 degrees. Therefore, the steerable angle of the main beam will be limit to ±9.66 degrees. To extend the steering range of the main beam in the far field pattern, we apply the optimization approach to design aperiodic optical phased arrays by optimizing the spacings between the adjacent antennas in the OPA. For proof of concept, we first design the aperiodic OPA with 32 optical antennas. The antenna spacing is limited to be in the range of 2.2 μm to 6.6 μm in order to meet the requirements of design rules and to have compact size. This structure can not only increase the steerable angle, but also reduce the limitation of fabrication resolution. It could efficiently suppress the grating lobes appearing in the far field pattern of a uniform OPA. The design was successfully tapped out for manufacturing. The PSLL for 32 antenna aperiodic optical phased array is 9.40 dB with a FWHM of the main beam of 0.65 degree without beam steering. The maximal steering angle can be extended to 51.8 degree. The increased steering range is important for the practical applications of optical phased array to the LiDAR systems. We obtained slightly better PSLL for the 32-antenna aperiodic OPA than the prior research, as shown in Table 6-1.

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| Table 6-1: Comparison of aperiodic optical phased array | | | | |
|  | This work | This work | D.W. Zhuang 2018 [40] | He, X., 2021[16] |
| Number of Antenna | 32 | 128 | 32 | 1024 |
| PSLL (dB) | 9.4 | 12.01 | 8.52 | 20.5 |

The optimization scheme is also applied to aperiodic OPAs with a larger number of optical antennas. Instead of optimizing the whole OPA, we divide the OPA into 2 or 4 groups. The optimization is applied to one of the groups to obtain the antenna spacings, which is imaged to layout the spacings for the other group. The maximal steering angle is 51.48 degree with a PSLL of 10.03 dB for a 32-to-128 imaged antennas. The 64-to-128 imaged antennas can achieve a maximal PSLL of 11.89 dB at the maximal steering angle of 52.7 degrees.

**6.2 Future Work**

In this work, we primarily work on side lobes suppression and the beam steering of the optical phased array. The next step that needs to be realized is to exploit the experiments to justify the simulation results. In practical experiments, phase correction to suppress side lobes may consume a lot of time. Therefore, it is necessary to make the measurement process automatically and control the environmental factors. During the experiments, the device is easy to be influenced by environmental factors. The group correction scheme can effectively correct the phase to obtain a clean narrow beam for optical sensing.

Because the steering range of the main beam of the uniform optical phased array is limited to the first side lobes, we designed an aperiodic optical phased array to suppress side lobes and increase the steering range. In the future design of aperiodic optical phased array, higher PSLL needs to be realized. That is, the ratio of the main beam and the max side lobe in the far field have to be larger. It is necessary to realize an optical phased array with a larger number of antennas. Therefore, the main beam in the far field of an optical phased array with a larger number of antennas will also be more concentrated.

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