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Integrated photonic beam steering architectures for broad band microwave and optical system

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**Politecnico
di Bari**

Department of Electrical and Information Engineering

ELECTRICAL AND INFORMATION ENGINEERING Ph.D. Program

SSD: IINF-01/A–ELECTRONICS

Final Dissertation

**INTEGRATED PHOTONIC BEAM STEERING ARCHITECTURES
FOR BROADBAND MICROWAVE AND OPTICAL SYSTEM**

by

Rahuldas Kutteeri

Supervisors:

Prof. Vittorio M.N. Passaro

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Prof. Mario Carpentieri

Course XXXVIII, 01/04/2023-31/03/2026



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Abstract

Beam steering will be important to future sensing and communication systems including phased-array radar, light detection and ranging (LiDAR), free-space optical communication, and 6G wireless systems. Conventional beam steering systems based on mechanical scanning or electronic phase shifting systems suffer from limitations such as limited speed, beam squint in broadband applications and high system complexity. Microwave photonics (MWP) is an alternative technology for broadband signal processing in the optical domain. Its advantages include low propagation loss and immunity to electromagnetic interference. The rapid progress of photonic integrated circuit (PIC) technology provides the possibility of integrated, compact, and scalable photonic beam steering systems.

This thesis addresses the design and execution of integrated photonic beam steering, which covers a range of topics from delay-domain to phase-domain and radiation-domain beam steering. The first part of the work presents a study of delay-domain beam steering enabled through photonic true time delay (TTD) architectures. In this regard, programmable delay lines using phase-change material-assisted Bragg gratings are used to show the design of microwave photonic antenna arrays with time-invariant beam patterns. The second part discusses phase-domain beam steering with optical phased arrays, where the beam direction is determined by a phase gradient across all emitters that interfere constructively in a given direction. The final focus is on radiation-domain beam steering using grating-based optical antennas, including an investigation of the potential for chirped grating coupler antennas to enable higher spectral bandwidth and beam quality over their uniform counterparts. A careful analysis arrived at an optimal value of a chirp increment of 0.75 nm. It provides a good compromise between bandwidth and beam focusing. The spectral bandwidth is now 81.54 nm compared to 19.3 nm for uniform gratings. The beam directivity can be increased by employing many antennas in parallel. Two-dimensional beam steering is possible through wavelength-dependent radiation and by controlling the phase of the excitation. The results show integrated photonic beam steering via combinations of true time delay beamforming, optical phased arrays, and radiation-engineered grating antennas as a generalised, compact, and scalable broadband steering platform for future photonic communications and sensing systems. Fast rise time makes CGA suitable for LiDAR applications as well.

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Chapter 1

Integrated Photonic Beam Steering: Foundations for Delay-, Phase-, and Radiation-Domain Control

1.1 Motivation for Integrated Photonic Beam Steering

The Control of the spatial direction of the electromagnetic radiation is the basis for many communication and sensing applications [1]-[6]. Beam steering, thus allows an electronically controlled antenna system to guide its antenna pattern electronically in a certain spatial direction, without mechanically moving the antenna. Applications occur in free-space optical communication, LiDAR, remote sensing, radar imaging, and high-capacity wireless communication. The rapid expansion of fifth generation (5G) and sixth-generation (6G) mobile communication networks has resulted in increased demand for efficient beamforming methods and systems in wireless networks at frequencies in the millimetre-wave (mmWave) and sub-terahertz (sub-THz) frequency band. The larger spectral band available when compared with ordinary microwave bands translates to higher data rates, lower latency, and high-density network capacity for applications such as autonomous vehicle networks, engaging virtual and augmented reality, and large-scale Internet of Things (IoT). However, mmWave transmissions are still limited by free-space path loss, atmospheric attenuation, and scattering and absorption in the presence of objects such as buildings and foliage. Hence, the need for highly directional transmission and reception to establish high reliability communication links with efficient utilisation of the available spectrum [1]-[4].

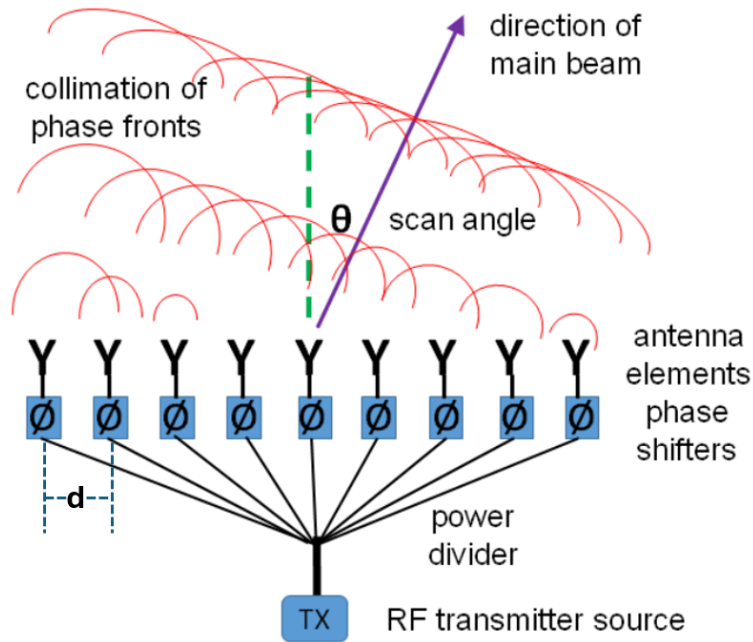


Fig.1.1. Linear PAA beam steering, where constructive interference of radiated waves determines the direction of the main beam. Here TX (transmitter) and θ direction due to input phase of ϕ [10]. Antenna elements are separated by a distance 'd'.

Phased array antennas (PAAs) overcome these problems of propagation by a directional antenna beam, which can be shaped by controlling the phase (ϕ) of each individual antenna unit/antenna elements. In an antenna array, the individual antenna units are applied with a particular phase or delay, so that the superposition of the individual electromagnetic waves is constructive in the desired direction, and destructive in other directions (Fig.1.1). By varying the excitations (phase) of the individual array elements, the direction of the main lobe (θ) of the antenna pattern can be adjusted electronically, allowing the field to be scanned rapidly from one part of the coverage area to another, without any mechanical rotation of the antenna. These principles of beamforming are used in radars, wireless networks, and sensing systems [6]-[8]. In most implementations, beam steering is accomplished with electronic phase shifters, devices that add a progressively larger phase shift to the signal going to each successive antenna element, relative to a reference element. Such a technique works well in narrowband systems, however in broadband systems where the phase depends on the wavelength or frequency,

changing the operating frequency of the antenna array requires a proportional change in the effective phase shift per unit distance across the array, thus changing the beam direction (this is otherwise known as beam squint, Fig.1.2) and distorting the radiation pattern across the array. In Fig.1.2 the direction of the beam corresponding to a particular frequency f_0 , was Θ_0 as the frequency changed from f_0 to $f_0 + \Delta f$ beam direction also changed to $\Theta_0 + \Delta\Theta$, thus limiting the bandwidth of conventional phased array architectures [2], [5], [9].

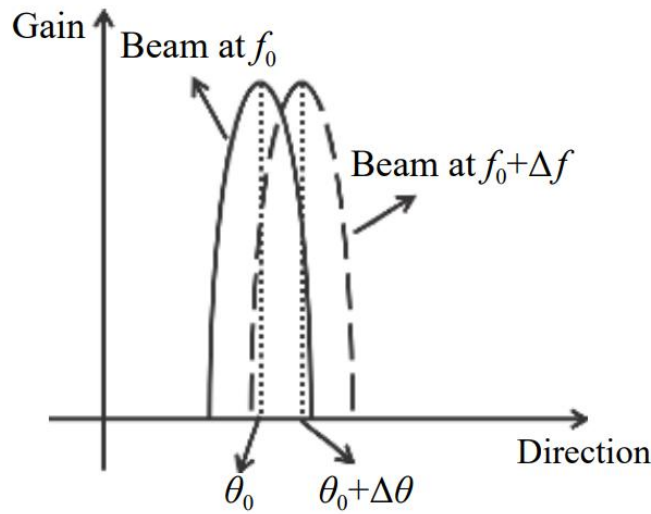


Fig.1.2. Schematics of beam squint for a beam at frequency f_0 [11].

MWP technologies are considered as an attractive solution for developing broadband beamforming devices, as they offer the advantages of optical signal processing technologies. In photonic beamforming, RF signals are modulated onto optical carriers which are then distributed over optical waveguides. These carriers have precise time delays imparted onto them via the waveguides to each antenna element. The optical delay is subsequently removed, the delays are processed in the electrical domain and the signal is fed to the antenna array (Fig.1.3). A photonic beamforming architecture can operate in both transmit and receive modes, as shown in Fig.1.3 (a) and (b) respectively. In the transmit mode, the RF signal modulates the optical carrier, which is then broadcast by a photonic beamforming network comprising a set of optical paths with controlled time delays. These RF signals are coupled into RF antennas which produce a steered radiation pattern. During reception, the signals from

the individual antenna elements are converted to optical signals, passing through the same delay network to account for the differences in propagation delay. The RF signals are combined to form a coherent beam. Optical signals can also be used for true time delay (TTD) beamforming, where the beam steering is performed by a change in the signal propagation delay. TTD beamformers are frequency independent, leading to broadband beam steering without the beam squint effect, which can occur in phase shifters. Besides their broadband steering capability, photonic beamforming architectures have very large bandwidth, low-loss signal distribution, and immunity to EMI, and enable integrated photonic beamforming networks [12]-[16].

The rise of the PIC (Photonic Integrated Circuit) has increased interest in beamformers based on photonic circuits. Devices such as optically tunable delay lines, modulators, couplers and photodetectors can now be integrated on a single PIC, allowing complex beamforming networks to be realised in a compact and stable platform with a reduced device footprint. Silicon-on-insulator (SOI) technology has attracted attention due to a combination of a large optical confinement, a high refractive-index contrast and its compatibility with the complementary metal-oxide-semiconductor (CMOS) fabrication technology. This compatibility eases large scale integration of optical circuits, such as optical delay networks, enabling very accurate steering of beam direction. Recent years have seen the development of a variety of photonic beam steering technologies, including delay-domain beamforming using integrated TTD networks, phase-domain beam steering using optical phased arrays (OPA), and radiation engineering using wavelength-dependent optical antennas such as grating couplers (GCs). All the techniques have their advantages and trade-offs in terms of bandwidth, steering range, scaling and complexity. Understanding the beam steering techniques is key for the next generation of the integrated photonic beam steering systems [19], [20].

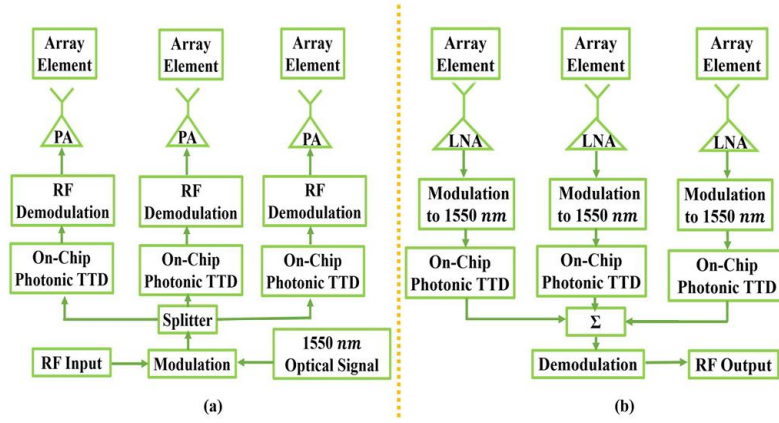


Fig.1.3. Photonic beamforming architecture in which RF signals (a) are modulated onto optical carriers, processed through optical delay networks, and (b) converted back to electrical signals for antenna excitation. [18].

This has spurred growth in integrated photonic beam steering approaches that could overcome drawbacks in electronic beamforming, while enabling miniaturized, scalable, and broadband beam steering capabilities. Recent advances in PICs, paired with newly proposed beam steering architectures, can potentially lead to the development of high-performance integrated optical systems targeted for use in future communications and sensing applications. The work described in this thesis mainly focuses on such integrated photonic beam steering techniques as delay-domain control, phase-domain control, and radiation-engineered optical antennas.

1.2 Fundamentals of Beam Steering and Phased Arrays

The principle of beam steering is the controlled interference of the electromagnetic radiation generated by antenna elements that are separated in space. With a single antenna element, the radiation pattern of an antenna is determined by the physical structure made up of its parts and the distribution of currents at the parts. When antennas elements are assembled together in an array to form an array antenna, the radiation pattern of an antenna array is a combination of the radiation pattern of all the individual antenna elements and the radiation pattern of the spatial configuration of the antenna elements in the array. The radiation pattern of an antenna array can be modified by varying the excitation of each individual antenna in the array. An important

application of this principle is in PAAs in the radar, wireless communication, satellite communication, and sensor domains, where fast and precise electronic beam steering is required [6]-[8].

The antenna elements of the PAA are spaced at uniform intervals in a linear or planar array. All the elements are fed in phase with equal amplitude; then the radiation from all the elements adds or reinforces in a direction perpendicular to the plane of the array, creating a radiation pattern with a main lobe broadside to the array (as shown in Fig.1.1). By adjusting the phase of the signals applied to adjacent array or antenna elements, the direction of the constructive interference in the resulting array pattern can be steered off broadside, as desired. The radiation pattern (or antenna pattern) of an array can be modelled by the so-called array factor, which describes the interference between the antenna elements due to their geometry and the mode of excitation of each element. The array factor for a linear array of N identical elements spaced ‘ d ’ apart is:

$$AF(\theta) = \sum_{n=0}^{N-1} e^{jn(k_0 d \sin(\theta))} \quad (1.1)$$

In Eq.(1.1) the free-space wavenumber is $k_0=2\pi/\lambda$, d is the spacing between successive elements and θ is the angle from the array normal to the observation point. This shows that the far-field pattern depends on the phase difference between the adjacent elements as a function of the observation angle and operating wavelength. Thus, there is a progressive phase shift. When $\Delta\phi$ is applied to neighboring elements, the $\sin(\theta)$ term in Eq.(1.1) becomes $\sin(\theta + \Delta\phi)$. Constructive interference occurs when the phase inside the exponential approaches zero, meaning the angle of the resultant primary radiation beam is equal to that of the beam steering relation, $k_0 d \sin(\theta + \Delta\phi) = 0$. This can be rearranged to yield the steering angle as:

$$\theta = \sin^{-1} \left(\frac{-\Delta\phi}{k_0 d} \right) \quad (1.2)$$

As a result, the setting of the required steering angle for the array will be determined by the progressive phase difference applied across adjacent antenna elements. The radiation beam can therefore be electronically steered across a continuous range of angles by varying the progressive phase difference, without the need for any physical movement of the antenna. The resolution, or angular resolution, of an antenna can be increased by using more antenna elements, which increases the overall size of the aperture to produce a narrower main lobe. The radiation pattern emitted from an antenna array will show secondary lobes, known as side lobes, whose amplitude depends both on the exciting distribution and the array shape. Phase-controlled arrays for beam steering are not ideal in wideband applications. Phase shift is a function of wavelength, so if a signal varies in frequency, the shift, and thus the angle of beam steering, will also change, compromising performance. The result is that the various spectral parts of the signal that is transmitted travel in slightly different directions, thereby causing the previously mentioned beam squint. It is possible to suppress this by using true TTD beamforming, in which the time delays rather than the phase shifts are applied between the various elements of the antenna array, causing the steering angle to become frequency-independent [12], [14].

The principles of phased array beam steering discussed above are the basis of a range of advanced photonic beamforming architectures operating on an integrated platform, including MWP beamforming systems on optical delay lines and integrated OPAs using phase shifters to control the excitation of radiating elements, as a means of steering the beam. Thus, an understanding of the relationship between phase control, array geometry and radiation patterns is important for the practical realization of photonic beam steering architectures. These have been useful in next chapters for implementations of beam steering architectures using integrated photonics, including delay-domain beamforming networks, phase-controlled OPAs, and GC antenna arrays.

1.3 Limitations of Conventional Beam Steering Techniques

The fundamental principles of phased-array beam steering systems have previously been described. However, due to the restrictions of conventional architectures, an application of a broadband communication system is not practical. Conventional architectures can be divided

into mechanically steered and electronically steered timed aperture phased-arrays. Mechanical beam steering or opto-mechanical, uses either gimbals or rotating mirrors to mount antennas, as well as using MEMS (microelectromechanical systems) devices (Fig. 1.4). The latter configuration is based on micro-actuated mechanical elements which produce changes in the position of radiating or reflecting elements, thereby leading to beam steering. This configuration may allow for larger steering angles, but is intrinsically limited by mechanical inertia, switching speed, and reliability of the mechanical components over time.

Electronic beams-steering techniques are based on the control of the phase of the excitation of the radiating elements in an array. For this reason, the form of the radiated wavefront is defined by the relative phase of the signals fed to the different antenna elements in the aperture. The two most widely used antenna architectures for active radar systems are the passive electronically scanned arrays (PESAs) and the active electronically scanned arrays (AESAs) which are schematically highlighted in Fig. 1.5(a) and Fig. 1.5(b), respectively. The PESA architecture (Fig. 1.5(a)) is based on a common transmitter driving the whole antenna array through a chain of power dividers and electronically controlled phase shifters, allowing one to scan the beam by changing the phase delayed to each of the individual antenna elements (see AESA architecture (Fig. 1.5(a), 1.5(b))). The transmit/receive modules are integrated in each antenna element with independent control of amplitude and phase, but the beam synthesis and beamforming designs are more flexible.

Mechanical, or gimballed steering is done by physically moving antennas, reflectors or optical surfaces to provide the desired beam direction. It can provide a very wide steering angle and high power output, but mechanical movement places speed and reliability limitations on how long a mechanical beam steerer can be operated. Furthermore, such systems are typically large and prone to mechanical wear and failure, limiting their use in applications requiring fast beam steering and high scanning rates such as light detection and ranging (LiDAR) or high-speed wireless communication systems. The demand for compact, high-speed beam steering systems means that existing systems with purely mechanical architectures are becoming less suitable for next generation sensing and communication applications [1], [3], [21], [25].

Electronic phased arrays are superior to mechanical systems in their ability to steer the beam quickly or continuously. Instead of mechanically tilting the array, each element of the array is

fed via phase shifters in the signal path to achieve the required amount of phase difference across the array. Phase shifting allows the beam to be steered electronically. Due to its faster scanning speed compared to conventional mechanical beam steering and provision of flexible systems, this technique is widely used in radar systems, satellite communication terminals, and other modern wireless communication systems [6]- [8], [23],[25]. Since broadband signals are typically used, the performance of phase-controlled beam steering can be limited by the frequency dependent phase shift due to beam squint. Because the phase progression measured is proportional to wavelength, the steering condition of Section 1.2 becomes dependent on frequency. When wideband signals are transmitted with phase-based array antennas, the different frequencies making up the signal will experience different phase progressions across the individual antenna elements. Thus resulting of mis-pointing of the main radiation lobe across the array bandwidth.

The beam squint problem is particularly important in modern wireless communication systems when they operate in the mmWave frequency range, where the signal bandwidths, and thus the communication data rates, are very large. This causes beam squint to degrade the communication performance by reducing effective gain in the desired direction and increasing interference with neighboring spatial channels. Furthermore, an additional limitation of electronic beamforming networks is the phase shifters used to steer the beams. The phase shifters introduce insertion loss, require power, and can be challenging to scale for large antenna array element counts. The required number of phase-shift circuitry components and calibration effort increases as the number of antenna elements in the array increases [12], [14].

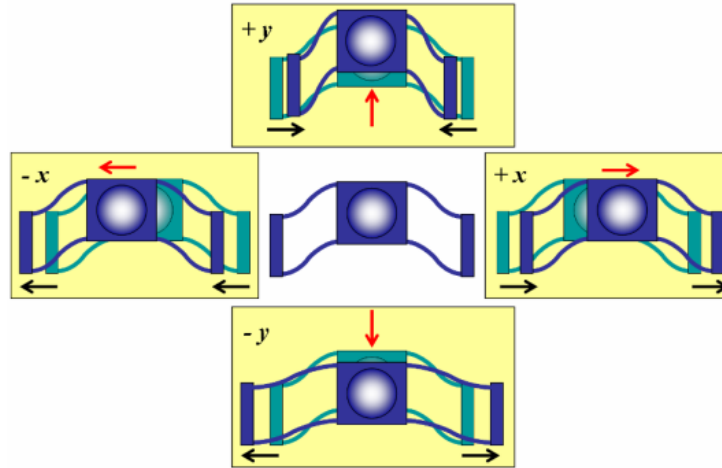


Fig.1.4. Principle of operation of 2D MEMS scanner. By combining these basic displacements, any point of the scanning area can be reached [151].

Another serious drawback of conventional electronic beam steering systems is that high frequency RF signals must be distributed along a large antenna array with minimal signal loss or distortion. In electronic beamforming structures, RF signals are conveyed to each antenna element through multiple phase shifters and a transmission line network, which causes substantial loss and phase distortion, especially at mmWave frequencies. These limitations exacerbate with more recent applications of large phased array systems, such as in advanced wireless communication and radar systems, where hundreds or thousands of antenna elements are required to achieve narrow beams and high resolution. Alternative architectures employing optical processing methods have become areas of further research in recent years. One possible candidate is MWP, which offers the ability to distribute and delay the RF signal in the optical domain, while benefiting from extremely large bandwidths and low signal losses [15], [16].

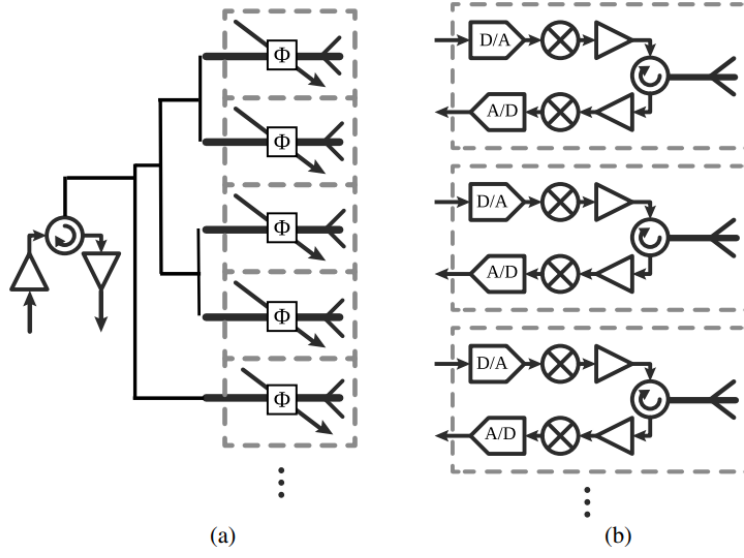


Fig.1.5. Schematic representations showing (a) a PESA, and (b). The arrows represent tunable phase and/or amplitude components. [27]

Recent research in integrated photonics has focused on beamforming architectures using optical delay networks and PICs, which can provide wideband beam steering with improved performance and reduced complexity. For example, a TTD beamforming architecture based on such devices is especially promising to overcome the beam squint limitation of phase-based array architectures. Instead of phase shifters, TTD systems consist of a number of time delays per antenna, and as a result can have a large bandwidth with the same steering angle. Optical delay lines based on micro-ring resonators, photonic crystal waveguides and switchable optical waveguide networks can lead to compact and wide-band optical beamformers [17], [19].

The limitations of mechanical and electronic steering methods have driven the development of alternative beamforming architectures based on photonic signal processing, allowing for integrated photonic beamformers that take full advantage of optical delay generation to provide broadband beam steering with far greater scalability and substantially less signal loss than their electronic counterparts. These advances have led to interest in MWP beamforming architectures and integrated photonic delay networks, which will be discussed next.

1.4 Microwave Photonic Beamforming Architectures

The limitations of conventional electronic beam steering systems described in the previous section motivate the need for alternative signal processing techniques capable of providing broadband beamforming. One approach to meet this demand is the use of MWP to implement beamforming systems to take advantage of the high bandwidth and low loss characteristics of optical communication with RF signal processing. MWP beamforming is a method of beamforming of RF signals in which the signals are modulated onto optical carriers and distributed on optical waveguides, optionally delayed or phase shifted in optical waveguides, and then converted back to RF to be applied to integrated radio electronics (IREs) of each antenna element. With the RF processing having been transferred to the optical domain, the very large optical bandwidths available with photonic devices can be exploited and some of the signal distribution bottlenecks associated with electronic systems can be circumvented [14]-[16].

An optical source, usually in the form of a laser, is used to generate an optical carrier, which is modulated by the RF signal using a modulator such as a Mach-Zehnder modulator or electro-absorption modulator [28]-[31]. Typically, a photonic delay or phase control network is used to manipulate the signals before the modulated optical signal is converted back into an electrical signal by photodetectors and fed to the antenna array. After some post-processing to impose the desired phase or time delays, the modulated optical signals are distributed among the antenna elements through optical waveguides. The very low optical waveguide propagation losses compared to RF transmission lines allow MWP systems to distribute the signals to large antenna arrays without considerable loss [14], [17].

Depending on how the RF signal is distributed in optical domain and how the different optical delays are generated, various photonic beamforming architectures can be identified. In the centralised photonic beamforming architecture, an RF signal modulated onto an optical carrier is distributed to all the antenna elements using an optical delay network (ODN) providing the required phases or time delays [31], [32] (Fig.1.6). In these architectures, beamforming is performed at a centralised optical processing unit, or may be implemented in a distributed way through the use of PIC incorporating optical delay lines and optical couplers on a single chip.

Such architectures offer the possibility of improved miniaturization and scalability which enable larger beamformer networks to be realized in a single compact device with greater stability and smaller footprint than on discrete optical components [19], [33].

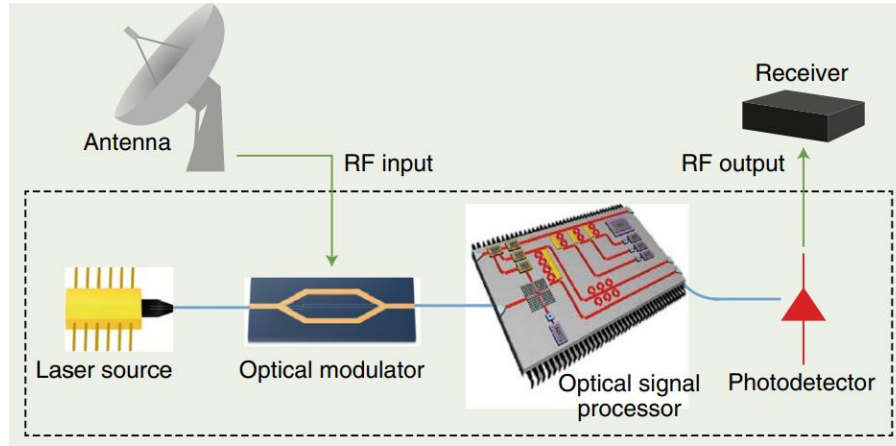


Fig.1.6. Block diagram showing the integration of RF modulation, an optical delay network, and high-speed photodetection for broadband signal distribution to an antenna array. [37]

One of the most important advantages of MWP beamforming systems is their large bandwidth. Microwave electronic beamforming networks that process microwave signals are ultimately limited by the physical dimensions of RF phase shifters and transmission lines. In photonic microwave beamforming systems, the signal is distributed and delayed in the optical domain where many tens of gigahertz, or even hundreds of gigahertz, of bandwidth are available [34], [35]. Another benefit is that large bandwidth is available, which is useful for mmWave and sub-terahertz communication systems where higher data rates require larger bandwidth signals. Furthermore, there is no EMI in optical signal distribution, which can improve the performance in complicated communication environments. In this regard, MWP beamforming has attracted the attention of researchers for its application to phased array radar, satellite communication systems and the next generation of wireless communication systems [36]-[38].

Recent advances into integrated photonic components, such as the MWP beamformer, has allowed the integration into a single beamforming chip of an ODN, modulators and photodetectors. PIC based on SOI, or alternative material platforms like Lithium Niobate on

Insulator (LNOI) and Silicon Nitride-on-Insulator (SiNOI), allow the integration of highly complex ODNs using well-established semiconductor wafer fabrication processes. Integrated beamforming chips have several advantages over discrete beamforming chips, such as reduced size, reduced power and more stability and scalability in their implementation and functionality. Most notably, integrated optical delay networks have been proposed for broadband beamforming for large antenna arrays, such as via micro-ring resonators, photonic crystal waveguides, and tunable optical delay lines [19], [39].

The performance of photonic beamforming systems is strongly governed by the underlying delay-generating mechanism in the optical network, with phase-based architectures still suffering from the undesirable wavelength-dependent steering behavior of electronic phased arrays. Therefore, many modern photonic beamforming systems use TTD architectures where the broadband optical delays are placed between the antenna elements to provide frequency-independent formation of the antenna beam, and these architectures will be the basis of many modern state-of-the-art MWP beamforming systems, as will be described in the section below.

1.5 True Time Delay Beam Steering

However, the previous section has shown how these architectures can offer a viable alternative to conventional electronic beam-steering systems, due to the ability to manipulate RF signals in the optical domain, the performance of these systems is mainly determined by how the relative excitations of the antenna elements are controlled. For example, in phased array systems, the beam can be steered by changing the phase of adjacent antenna elements in a progressive way. Although this method offers rapid steering, it has a limitation with broadband signals because the phase shift is dependent on wavelength: the needed phase slope between two points in order to steer the beam is different for different frequencies. Since different frequencies present in a broadband signal have distinct effective phase slopes across the array, thus a different direction of propagation, beam squint occurs. This results in the distortion of the radiation pattern and a degradation of the beam pointing accuracy across the operating bandwidth [12], [13].

Beam squint becomes a major, limiting issue in modern wireless, communications and radar

systems operating at mmWave and sub-terahertz frequencies where a very wide signal bandwidth is required for augmented data rate and advanced sensing applications. Due to the short wavelength, a small frequency detuning leads to a meaningful steering angle change. This limits the power gain in the desired direction while causing radiation to undesired angular channels. As a result, phase-based beamforming architectures are generally not suited for applications requiring broadband performance and a fine resolution of the beam shape. In this case, TTD beamforming can be used. In TTD, the relative time delay between the signals of each pair of antennas is controlled, rather than the phase difference. Because time delay does not depend on the signal wavelength, the steering direction is constant across the entire signal bandwidth, solving the beam squint effect that limits conventional phase-based arrays [14], [15], [40], [41].

To understand the principle of TTD beamforming, let us consider the propagation of an electromagnetic wave from an antenna array with element separation, d . To steer the beam in a direction away from the array normal at an angle α , the delays between adjacent elements in the array must be as defined in the following expression so as to form a beam of constructive interference in that direction:

$$\tau = \frac{d \sin \alpha}{c} \quad (1.3)$$

Here in Eq.(1.3), τ is the time delay applied between each individual array element, and c is the speed of light in free space. This implies that the time delay needed to steer the beam is independent of wavelength, depending only on the array geometry and the direction in which the beam is aimed. Since all frequencies experience the same delay, a broadband input signal propagating through TTD beamforming network will be radiated in the same direction for all frequencies present in the input signal (Fig.1.7). This key property makes TTD beamforming particularly suited for broadband communication and sensing systems where the beam direction needs to be the same for all frequencies.

MWP is also well-suited to TTD beamforming due to the range of optical signal-processing techniques that can introduce wide-bandwidth, high precision time delays, with low signal losses. In a photonic TTD system, the RF signals are in the first instance modulated onto optical

carriers which are then passed through an optical delay network to introduce time delays before being converted to electrical signals that drive the antenna elements. There are many implementations of optical delay lines, including optical fiber delay lines and integrated devices, such as integrated waveguide delay lines, micro-ring resonators, photonic crystal structures, and switchable delay paths. These implementations can be realized as a large, continuous and tunable optical delay line, with low insertion loss and high bandwidth [16], [42]-[44].

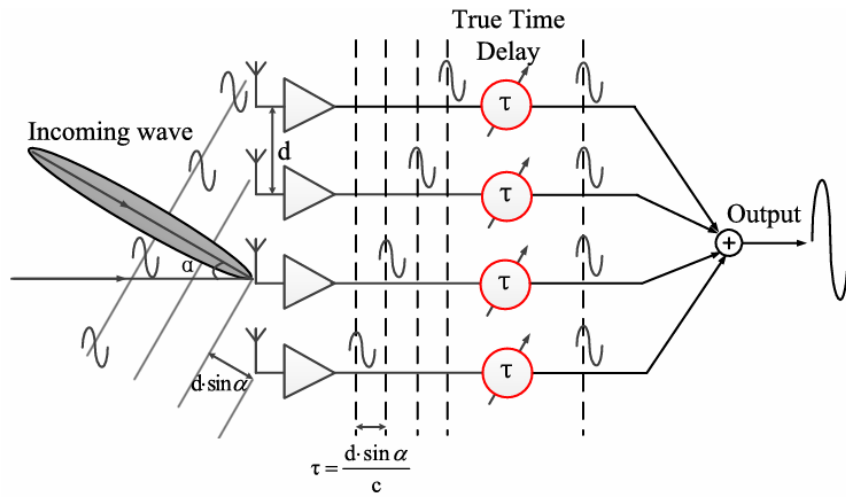


Fig.1.7. TTD architecture as used for wideband beam steering in a timed-array receiver, where α is the steering angle. [50]

In addition to minimizing beam squint, photonic TTD beamforming provides advantages compared to conventional electronic delay networks. The low propagation loss of optical waveguides and optical fibres allows power-efficient distribution of signals to many thousands of antenna elements over a long distance at negligible losses. Photonic delay networks are immune to electromagnetic interference which is an important characteristic for complex communication environments [45]-[49]. Additionally, recent advances in photonic PIC technology have eased the design and implementation of a TTD beamformer on a chip with a compact architecture further reducing its size and power requirements. Integrated MWP beamforming chips which integrate the optical delay lines and optical switching networks with

tunable optical delays will enable broadband, beam-steering optical communication and sensing systems with unprecedented functionality and flexibility [19].

The recent progress of integrated photonic technology has rekindled interest in TTD beamforming as a means for implementing high-performance beam steering systems, which can distribute optical delay networks in combination with PIC in scalable beamforming architectures, thus enabling very large antenna arrays and extremely wide signal bandwidths. The possibility to develop compact high-performance delay generation mechanisms integrated in PICs has led to the proposal of several integrated optical delay technologies, including micro-ring resonators based delay networks as well as photonic crystal waveguides and tunable optical waveguide structures. These technologies form the basis of modern integrated photonic beamforming systems, which are introduced in the next section.

1.6 Integrated Photonic Delay Line Technologies

The previous section provided the fundamentals of TTD beam steering, which is of interest because it enables frequency-independent beam steering of broadband antenna array systems. A critical requirement for accomplishing TTD beamforming is the generation of precise and controllable delays between the signals feeding each of the antenna elements. Large free-space optical components and long lengths of optical fibre were typically used in early MWP implementations of TTD beamforming. More recently, a new class of compact and scalable delay lines amenable to PIC implementation has been developed. Integrated photonic delay lines are one of the main areas of research in MWPs, as they are a key enabling technology for broadband photonic beamforming systems for high-performance large antenna arrays. [16], [17], [44], [51], [52].

Optical fiber delay lines were the first type of network employed in MWPs for time delay. In these systems, the optically modulated radio frequency signals are transmitted through optical fibers of different lengths before photodetection. Low propagation loss and large values of time delays make fiber-based systems attractive for early TTD beamforming networks. To achieve the required discrete delays corresponding to the different steering angle distributions, fibres of different lengths are used or optic switching networks are used to route light through

different optical fibre delay paths. However, the downsides, such as systems architectures that are not reconfigurable or compact enough to be practical, have prevented fiber delay lines from being widely adopted in modern optical integrated beamforming networks in spite of their advantages. A large amount of work has therefore been devoted to implementing delay generation techniques directly in PICs [15], [16], [53]-[56].

Waveguide delay lines can be regarded as a natural extension of fibre-based delay architectures, where a long-fibre segment is replaced by waveguides fabricated on PICs. In this case physical delay is created by varying the propagation length of optical waveguides on a PIC. Integrated delay lines are commonly implemented on SOI [57]-[59], silicon nitride (SiN) [60]-[64], lithium Niobate on insulator (LNOI) [68], [69], [79] and indium phosphide (InP) [65], [66] PIC platforms (Fig.1.8). Switchable optical delay networks comprising cascaded waveguide paths and optical switches have been proposed to achieve reconfigurable delays, selected according to a desired steering angle of the beam. Thus, although these architectures are compact and have a high potential for integration when compared to fibre, they must still deal with the issue that the delay is proportional to the length of the waveguide, so long and hence large area waveguides may be necessary to achieve high delays, and they also have important propagation losses [19], [67], [70]-[76].

A number of studies have focused on resonance-based delay structures that avoid the problems of long physical delays. Micro-ring resonators, for instance, produce large optical group delays near resonance due to the very high dispersion present in the micro-ring resonator. A suitable choice of resonator parameters and coupling conditions between the micro-ring resonator and the bus waveguide can provide a tunable optical delay function with compact footprints. Furthermore, thermal or electrical tuning of micro-ring resonators enables reconfigurable photonic beamforming networks. These advantages have motivated the development of micro-ring-resonator-based delay architecture as a promising platform for implementation of integrated MWP systems. The resonance-based nature of such structures often leads to a relatively low delay-bandwidth product, and also makes them sensitive to fabrication tolerances and temperature changes, which needs to be taken into account in practice [77]-[80].

Another promising approach for achieving large optical delays within a small integrated device is the use of slow-light structures, with photonic crystal waveguides being particularly attractive. In photonic crystal waveguides or photonic crystals generally, the photonic band structure is achieved by adding a periodic perturbation to the refractive index in one direction.

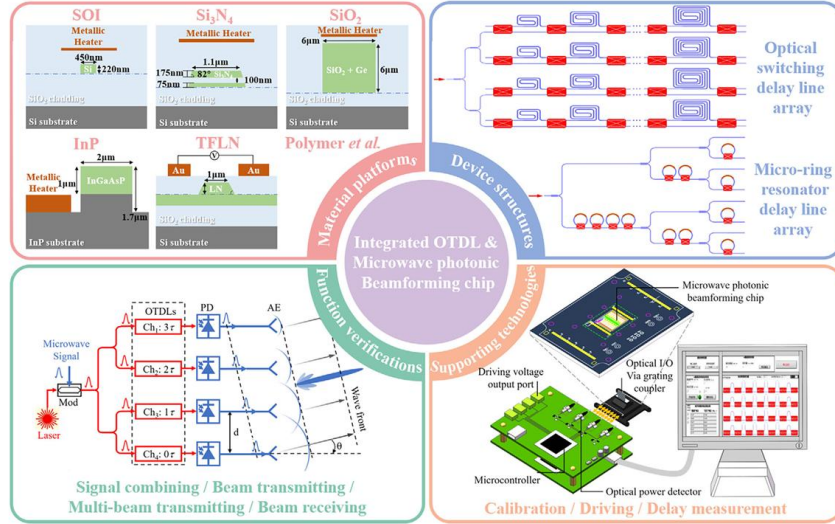


Fig.1.8. Overview of the integrated optical time delay line and microwave-photonic beamforming chip with insets showing material platforms, optical time delay line array structures, supporting calibration/driving/delay-measurement modules, and the experimental beamforming setup. [44]

This can lead to very large delay times at very small physical lengths, which makes photonic crystal waveguides very attractive candidates for integrated delay lines. By choosing the dispersion relationship, the delay through a photonic crystal waveguide can be made large, while still maintaining a reasonable optical bandwidth. However, slow-light structures have a number of drawbacks: they are more sensitive to fabrication errors, have larger scattering losses, and larger dispersion, causing potential distortion of broad-band signals. Device designs and optimizations must be carefully tuned in order to balance delay performance with maintaining the signal quality of the photonic crystal delay system [81], [82].

Apart from delay elements, most modern MWP beamforming systems also rely on tunable optical delay networks which are collections of delay generation techniques capable of

implementing flexible, scalable beamforming networks. The network typically consists of cascaded optical delay lines, optical switches, tunable optical resonators or programmable PICs with the ability to change steering angles or operating conditions while remaining broadband in operation. PICs have achieved a high level of miniaturization that allows for these delay networks to be delivered on chip-scale platforms, which ultimately improves system stability while decreasing the overall footprint and allowing for large scale co-integration of associated photonic devices such as modulators, photodetectors, and other devices [83]-[85].

While there has been great progress in integrated photonic delays, there still remain issues to be resolved before practical delay networks can be developed for broadband beamforming systems. There are trade-offs between the amount of delay, the footprint, the optical loss, and the operating bandwidth of the photonic delays. Fiber-based delay lines are attractive because of their large delay, but they are bulky. Resonant and slow-light media have the potential to lead to small devices, but may have limited bandwidth or be sensitive to fabrication imperfections. Research into alternative architectures and hybrid combinations of different types of delay continue, with the goal of maximizing the advantages of each technique. Hence, efficiently integrated and scalable photonic delay technologies are an essential component of high-performance MWP beamforming systems, which are anticipated for next-generation systems for communications and sensing applications.

1.7 Optical Phased Arrays for Integrated Beam Steering

After having reviewed integrated photonic delay line technologies for beam steering, coming onwards will describe an alternative major method for beam steering in integrated photonic systems based on OPAs. Analogous to radio-frequency phased arrays, OPAs consist of a plurality of coherent radiators with independently tunable relative phase to shape and steer the radiation fields emitted in the far field [1]-[4]. In an OPA, optical radiation propagates through an array of waveguides, coupling to free space at radiators (for example a grating antenna or edge emitters). The radiation emitted from each of the radiators is phased with respect to each other such that constructive and destructive interference of the emitted radiation determines the direction of the emitted optical beam [86]-[89]. This provides a technique for optical beam steering without mechanical movement, resulting in very compact and fast optical beam

steering systems on integrated photonic platforms [6], [12], [13].

Integrated OPAs are under investigation due to their suitability for integration with silicon photonics and other materials for PICs [90]-[92]. An integrated OPA distributes a laser beam into several waveguides by means of optical splitters/couplers. Each waveguide includes a tunable phase shifter before the light radiates from the integrated OPA. The optical fields radiated from the array interfere at the far field into a directed beam, and the far field direction is set by the phase gradient across the emitter array [6], [12], [13]. The photonic integrated fabrication technology allows precise control of the waveguide geometry and the optical phase, so that large arrays of optical emitters can be fabricated on a small footprint chip [83]-[85]. This has led to the integrated OPA being considered a strong candidate for applications requiring miniaturized beam steering systems such as solid-state LiDAR, free-space optical (FSO) communication and imaging systems [1]-[4].

The most important component of an integrated optical phased array is the phase shifter, which is able to tune the optical phase of each emitter branch. There are many different phase tuning techniques that have been developed for integrated OPAs. The most commonly used phase shifter is the thermo-optic phase shifter [56], [93]-[95]. This consists of a region of the waveguide that is locally heated to change the index of refraction by the thermo-optic effect. Thermo-optic phase shifters tend to be easy to manufacture and are compatible with standard silicon photonics fabrication processes, but they tend to be limited by a relatively low speed and high power consumption. Alternative approaches employ electro-optic phase shifters such as lithium niobate or carrier-induced refractive index modulation in semiconductors for high-speed phase modulation [96]-[98]. Carrier injection or depletion phase shifters based on silicon waveguides, which are faster than thermo-optic phase shifters, cause additional optical losses or nonlinear effects [14]-[17].

Beam steering in OPAs can be accomplished by a controlled linear gradient in phase-shift applied to the different emitters in the array. By introducing a progressive phase-shift across adjacent emitters, constructive interference between the optical waves emitted by the emitters will occur in a direction corresponding to the array factor discussed in Section 1.2. In addition to steering by changing the phase, many integrated photonic beam steering systems achieve steering by using the angularly dependent emission pattern of the grating emitters. Steering in

these systems can be achieved by changing the optical wavelength incident on the emitter array. The reason for this is that the radiation angle of the grating antennas depends on the phase matching between the guided mode and the radiation field [99]-[102]. The two-dimensional beam (lateral and vertical, with respect to the chip surface) steering capability is achieved by modulating both the wavelength and the phase of each emitter in the array.

OPAs have therefore become a key solid-state beam steering technology. In particular, they have been used extensively in the development of compact solid-state LiDAR systems. Such systems require fast scanning and high resolution imaging without any moveable mechanical components, which can be particularly important for autonomous navigation applications [1]-[4]. Integrated OPA chips fabricated using silicon photonics platforms have already demonstrated large emitter arrays with both narrow beams and high angles of steerability while keeping a small foot print. Additionally, the scalability of PICs could allow the integration of hundreds or thousands of emitters on a silicon chip, improving the spatial resolution while improving the beam quality [83]-[85]. In addition, OPAs have been studied for use in free-space optical communication, optical wireless networks, and adaptive optical sensing systems (optical field measurement).

However, the presence of side lobes in the far-field pattern distribution is one problem that must be dealt with in practice. This can be attributed to the finite number of emitters in the array and the finite spacing between the emitters. Unwanted side lobes can ruin the quality of the beam and the efficiency of an optical system by directing optical power into unwanted directions [6], [12], [13]. Large arrays of optical phase shifters can lead to meaningful power dissipation and thermal management challenges, especially with thermo-optic tuning devices. Fabrication tolerances and phase errors can lead to distortions in the output beam pattern and require calibration and compensation to ensure accurate beam steering [83]-[85]. To address such challenges, research efforts in the field of integrated photonics have been focusing on improving phase shifter designs, optimizing the configurations of the arrays, and developing more advanced beamforming algorithms.

Overall, OPAs are a compelling optical beam steering technique that relies on coherent addition of multiple optical sources, which can readily be integrated on-chip using PIC technology. Applications in communication, sensing and imaging have been identified. Important

performance parameters include the radiation mechanism of the optical sources, since this affects the resulting beam quality and steering efficiency. This is particularly true for integrated devices, where the most often considered approach for coupling from guided to free-space emission are grating-based antennas. This section thus introduces grating-based optical antennas and radiation engineering principles, essential to integrated photonic beam steering architectures, and fundamental to the devices analyzed in this thesis.

1.8 Grating-Based Optical Antennas and Radiation Engineering

Analogous to the discussion above, OPAs make use of radiating elements that convert guided optical modes, propagating in waveguide structures, into free-space radiation. Numerous optical antennas have been developed in integrated photonics platforms; however, grating-based optical antennas have become some of the most developed and widely employed integrated photonic circuit (PIC) radiators due to their compatibility with planar PIC platforms and the high efficiency of free-space radiation coupling from waveguides [103, 104]. Grating antennas rely on a periodic perturbation of the waveguide refractive index or the waveguide geometry, such that the phase matching condition between the guided optical mode and the radiated optical wave propagating outside the waveguide is satisfied and part of the guided power can be radiated out of the plane, leading to a directional radiation pattern (Fig.1.9), periodic grating slots etched in a silicon waveguide scatter the optical mode guided in the waveguide. Interference of the generated waves in free-space at a particular angle forms an antenna beam around that angle. This type of antenna can be directly implemented in the PIC platform, allowing the realization of optical emitters in OPAs and integrated LiDAR systems [5], [6], [9].

In a grating antenna, the direction of radiation is determined by the phase-matching condition between the guided optical mode and the radiated field. The guided mode with effective refractive index, n_{eff} (average of the indices of the core, Si and the cladding, SiO₂ over one period) is propagating through a structure with a periodic index with unit cell period 'a'. Constructive interference of the scattered fields occurs when the phase mismatch along the scattering path between two scattering centers fulfils the grating equation:

$$\sin \phi = \frac{n_{eff} - \frac{\lambda}{a}}{n_{clad}} \quad (1.4)$$

In Eq.(1.4), ϕ is the radiation angle with respect to the normal of the surface, λ is the optical wavelength and n_{clad} is the refractive index of the medium in which the grating is immersed. We can see that the radiation direction depends on the grating structure and the optical wavelength. This result leads to grating antennas being able to provide wavelength-tunable beam steering, and has therefore been widely used in integrated photonic beam steering devices. By tailoring the grating parameters, it is then possible to control the radiation angle, beam divergence and radiation efficiency of the emitted optical beam.

The simplest configuration is the so-called uniform grating antenna (UGA) where the grating period does not change along the waveguide propagation direction. In this case, the phase matching is satisfied in the entire aperture at the given wavelength, thus the radiation is coherent and the antenna aperture may be treated as a single radiation source. As a result, UGAs are expected to produce focused radiation beams with relatively narrow divergence angles when excited at (or near) their design wavelength. Due to the periodic nature of the structure, the grating condition is only satisfied over a limited range of wavelengths [103], [104]. Furthermore, at frequencies different from the design wavelength, the corresponding radiation angle will deviate from the intended value according to the grating equation, which may also degrade the quality of the radiated field. This limits the usable bandwidth of uniform grating antennas and their applicability for broadband beam steering applications [5], [6], [9].

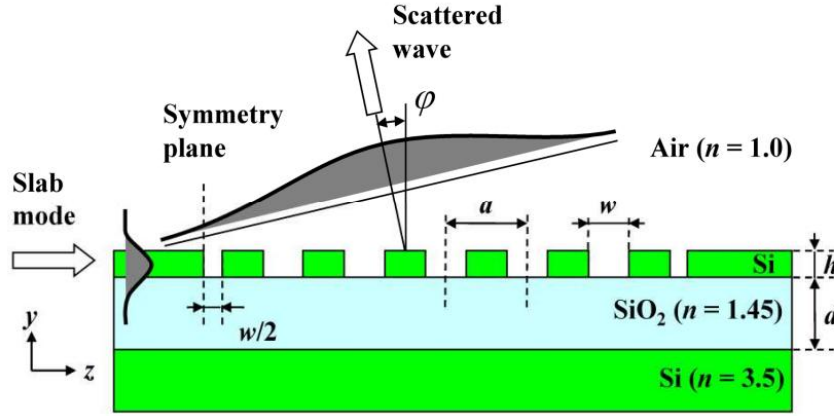


Fig.1.9. Schematic representation of the grating coupler. Light is transmitted from the TE mode of the slab waveguide on the left into the grating and the slots scatter the light into the fiber positioned at angle ϕ . In this figure the wave is scattered at a negative angle which appears in counterclockwise direction with respect to the grating normal. [125]

Chirped grating antennas (CGAs) have been proposed to overcome these limitations by using a radiating structure in which the grating period varies along the grating length in a controlled way so that the phase-matching condition can be satisfied at the different points along the grating for different wavelengths. The distributed phase-matching mechanism allows a wider range of wavelengths to be coherently added to the radiation field and therefore gives a wider bandwidth capability for the antenna [47], [48], [105]. Chirped gratings can also be used to control the shape of the radiation field and so improve beam shaping and the far-field radiation pattern. Chirped grating antennas could thus be used to obtain broadband radiation and improved beam quality within an integrated photonic beam steering device [90], [106], [107].

Apart from the bandwidth extension, the radiation pattern is the second most important factor for the performance of a grating-based optical antenna. It is natural to think that all characteristics of the emission pattern such as the beam width, directivity, and the level of the side lobes are determined by the radiation profile of the grating [37], [93]-[94]. Adjusting the grating period, duty cycle, etch depth, and refractive index contrast can control the strength of the coupling between the guided mode and the radiated field, which affects the amplitude distribution along the grating and, consequently, the beam shape. Apodization, chirped grating designs, and the use of multi-element antenna arrays have been investigated to reduce side

lobes and improve beam confinement in integrated photonic antennas [108]-[110].

Grating antennas also provide a second beam steering mechanism, namely tuning with respect to the optical wavelength. Because the radiation angle is wavelength-dependent, tuning the input wavelength will have a predictable effect on the radiation angle via the grating equation. The property of horizontal grating allows vertical steering without tuning the phase [99], [111], [112]. Combining wavelength-dependent steering with phase control in an optical phased array gives a two-dimensional steering of an optical beam. In these structures, the vertical emission angle can be controlled by the wavelength, while the phase gradient across the array can control the lateral angle [113], [114]. Both degrees of freedom have been widely researched for integrated photonic beam steering architectures, particularly for solid-state LiDAR and free-space optical communications, where compact size and fast steering of the emission beam is desired.

The coupling of this type of grating-based antenna to PICs can thus be an alternative platform for realizing optical beam steering systems, because the surface-emitting gratings exhibit out-of-plane radiation compared to edge-emitting waveguide-based antennas, which is more compatible with the integration to planar photonic chips and wafer-level fabrication. With the option of varying the radiation characteristics through design, grating antennas can be used not only as coupling interfaces but also as optical sources of radiation with the option of beam shaping or steering. As integrated photonic technologies advance, grating-based radiation engineering is expected to find further use in developing compact beam steering solutions in communication, sensing, and imaging applications. These physical principles are the basis for the implementation of radiation-based beam steering in the field of integrated photonics. Especially, the radiation pattern of grating antennas adds an additional degree of freedom to optical beam steering, next to the conventional phase-only control of optical beams for beam steering applications. It is directly relevant to the beam steering methods discussed by this thesis, in which engineered grating antenna structures are applied to the emission of broadband, high quality optical beams on integrated photonic platforms.

1.9 Research Gap and Thesis Motivation

In this section, we have covered the principles of beam steering, the limitations of conventional electronic beam steering and the prospects of photonic technologies for broadband beamforming. The MWP beamforming architectures are favorable when compared to their radio frequency (RF) counterparts in terms of extremely wide bandwidth, low-loss signal distribution and intrinsic immunity to electromagnetic interference. Recent progress in PIC technology has enabled small footprint optical systems for beamforming based on optical delay networks, OPAs and grating-based radiating structures. Nonetheless, several deficiencies still exist in current photonic beam steering systems, leading to active efforts to achieve broadband operation, high beam quality and high-level integration of PIC systems [14]-[17], [103], [104].

One of the major challenges for photonic beam steering systems is the realization of TTD beamforming architectures, which remove the effect of beam squint by adding frequency-independent delays on the antenna elements. However, such TTD architectures are difficult to realise: in practice, complicated delay networks with multiple optical delay paths or resonant delay structures produce additional insertion loss, larger footprints, and increased complexity in routing the optical signals in the generated integrated circuits. Furthermore, for large antenna arrays with wide beam steering range, the number of delay elements needed can be huge. This severely limits the scalability of delay-based systems, and is one of the major reasons why the development of compact and low-loss photonic delay structures is still an active research topic in MWP [12]-[15], [87], [104], [115].

OPAs have received wide-ranging attention for integrated photonic beam steering. By controlling the optical phase of multiple arrayed emitters, a beam can be actively steered without mechanical actuators, and OPAs can be fabricated using well-established photonic integration platforms such as silicon photonics. The performance of OPAs depends on the phase tuning mechanisms used and the spatial distribution of the array. Phase shifters based on thermo-optic or carrier injection mechanisms require a large electrical power input. Such phase shifters could be limited with respect to their tuning speed. Some commonly encountered limitations in most OPA realisations are beam divergence, the presence of side lobes in the radiation pattern due to the finite aperture of the array, and phase errors associated with fabrication tolerances, resulting in degraded beam quality and reduced steering ranges for

integrated OPAs [16], [89], [106], [116].

Coupling optical waves from waveguides to free space is another limiting factor in many integrated beam steering systems. Uniform grating antennas are by far the most common optical emitters in integrated photonic systems, as they provide efficient coupling of guided and radiated optical modes. The radiation properties of uniform gratings are optimised for one wavelength. In reality, gratings do not operate at just a single wavelength - as the wavelength changes the angle of radiation changes and the radiation grating becomes less coherent across the aperture. To circumvent this limitation of classical grating antennas, radiation engineering techniques such as chirped grating structures and optimized coupling profiles have been actively explored to improve the beam shaping capabilities and spectral response of integrated optical antennas [90], [105], [117]- [119].

Disadvantages associated with delay-based beamforming networks, OPAs and classical grating antenna designs highlight the need for next-generation integrated photonic beam steering systems capable of overcoming a number of design challenges. Photonic beam steering systems to be applied in diverse applications including LiDAR devices, free-space optical communication and advanced sensor systems will require components capable of broadband operation while maintaining compact integration, high quality beam forming capabilities, and good radiation efficiency. To achieve these goals, various beam steering domains in integrated photonic platforms are being explored in delay-based control of signal timing, phase-based control of optical interference, and radiation-based control of beam formation [19], [42], [47], [120].

These challenges and considerations gave rise to the present thesis on integrated photonic beam steering architectures investigated from three complementary directions. First, the use of integrated optical delay structures for the implementation of TTD beamforming networks (TTDBNs) which further support broadband operation is investigated. A second method of beam steering is OPAs, where the phased distribution of light from optical emitters is control assisted to obtain a phase-domain beam steering. Furthermore, radiation-domain beam engineering via grating antennas is a third method to manipulate the beam characteristics of the emanated light and to improve the beam quality and broad spectral bands. In particular, chirped grating antenna structures are examined for their ability to increase spectral bandwidth

and alter spatial output properties of the beam [121]- [124].

This work seeks to address some limitations of the current state-of-the-art photonic beam steering technology by considering these three complementary beam steering approaches within an integrated photonics platform. The delay-based beamforming approach, the phase-controlled optical array, and the radiation-engineered grating antenna together form a powerful toolbox towards the realization of compact and broadband integrated photonic beam steering devices for advanced photonic applications. The subsequent section presents the thesis objectives and how the conducted research is laid out in the following chapters.

1.10 Thesis Objectives, Contributions, and Organization

While the first part of this chapter has introduced the principles of beam steering, the limitations of conventional electronic approaches and the potential of integrated photonic technologies for use in broadband beamforming systems, the survey undertaken has revealed areas of continuing difficulty. Such areas include the complexity of delay-based beamforming networks based on arrayed waveguide gratings, limitations in phase-controlled OPAs and the bandwidth limitations of conventional grating antenna approaches. Consequently, research has been recently focused on alternative integrated photonic schemes with broadband, compact integration and good beam quality. The main goal of this thesis is to study the integrated photonic beam steering schemes which use delay-domain, phase-domain and radiation-domain approaches to realise scalable and broadband beam steering systems suitable for modern optical communication and sensing applications.

This thesis aims at the study and the design of integrated photonic structures for beam steering in PICs, in particular TTD beamformers, OPAs and grating-based optical antennas. These devices are studied in detail, and all these structures can be regarded as complementary beam steering domains on integrated photonic platforms, based on different physical principles. Delay-domain beam steering relies on introducing precise delays between the signals exciting multiple radiating elements, achieving steering that remains frequency-independent. Phase-domain beam steering, on the other hand, relies on manipulating the phase gradient in arrays of optical emitters to achieve real-time steering by constructive interference. Radiation-domain

steering is the use of optical antenna structures such as grating-based emitters to control beam profile and improve the radiation characteristics of the emitted radiation across a wide frequency range.

Based on the results presented in these individual sections, this thesis first presents designs of integrated photonic delay structures aimed at the implementation of broadband TTD beamforming networks. The designs presented are broadband over large bandwidths while also maintaining well-defined beam steering behavior. Second, the effect of phase control for beam steering via OPAs is studied, with an emphasis on how it changes the requirements that must be fulfilled by the emitter array and the beam pattern. Third, radiation engineering strategies for grating-based optical antennas are used to improve the radiation pattern and spectral bandwidth of integrated photonic emitters. The special case of chirped grating antennas is stressed, which allows distributed phase matching along the radiating aperture and provides greater spectral bandwidth than conventional uniform grating antennas. The study of these complementary approaches is expected to lead to the development of efficient, compact beam steering devices for integrated photonic platforms.

The thesis is organised according to these research goals, leading the reader from the topic of theory to the development of devices. Chapter 1 therefore focuses on the theory of beam steering and compares customary and photonic beamforming architectures in detail. This chapter discusses the limitations of electronic beam steering approaches and the motivation for integrated photonic approaches. Key technologies in photonic beam steering are discussed in more detail, including TTD beamforming, integrated photonic delay lines, OPAs, and grating-based optical antennas.

Chapter 2 introduces the topic of delay-domain beam steering by presenting the use of integrated delay structures for the implementation of TTD beamforming architectures. A discussion is given on the design and operation of optical delay networks to achieve a prescribed time delay between radiating elements in broadband and squint-free operation.

In Chapter 3, OPAs are applied to phase-domain beam steering in optical integrated emitter arrays. Beam parameters such as beam width, directivity, and steering range will also be discussed.

Chapter 4 introduces the concept of radiation-domain beam steering, i.e. imposing beam

steering to optical radiation using artificially designed grating antenna structures, with focus on chirped grating coupler antennas capable of broadband optical radiation and beam shaping. An analysis of the dependence of the radiation characteristics, beam quality and spectral bandwidth on grating parameters.

In the final chapter, the results of this work are summarized, presenting an outlook on future research directions for integrated photonic beam steering systems, and charting a path from a thorough examination of the physical principles of the different beam steering approaches to compact, large optical bandwidth, integrated photonic beam steering architectures.

Chapter 2

Delay-Domain Beam Steering Using Integrated Photonic True Time Delay

As discussed in Chapter 1, delay-domain, phase-domain and radiation-domain beam steering techniques are employed in integrated photonic beam steering systems. This chapter will describe the delay-domain beam steering technique in which true time delay networks provide frequency-independent beam steering across the bandwidth of the antenna array.

2.1 The need for TTD

Phased-array beams are steered by introducing a phase difference between the array elements which varies linearly along the array [126], [127]. As discussed in section 1.3, the main lobe steering condition for a linear array with spacing d is given by:

$$\Delta\phi = -\beta d \sin \theta \quad (2.1)$$

Here in Eq.(2.1), $\beta = \frac{2\pi}{\lambda}$ is the propagation constant, $\Delta\phi$ is the phase difference between adjacent elements, and θ is the steering angle. By applying a constant phase difference $\Delta\phi$ for a monochromatic beam, a well-defined beam direction can be achieved. In broadband systems, however, the propagation constant is frequency dependent according to the Eq.(2.2),

$$\beta(\omega) = \frac{\omega}{c} \quad (2.2)$$

In Eq.(2.2), ω is the angular frequency and c is the speed of light in vacuum. Hence, a constant phase increment results in different steering angles at different frequencies. The steering angle becomes:

$$\theta(\omega) = \sin^{-1} \left(-\frac{\Delta\phi}{\beta(\omega)d} \right) \quad (2.3)$$

which is explicitly frequency dependent. Hence it occurs beam squint, as explained in chapter 1, and frequency independent steering mechanisms should be implemented to eliminate the effect. With TTD, successive elements have a constant delay τ rather than frequency dependent phase shift. The steering condition for TTD can be written as,

$$\omega\tau = \beta(\omega)d \sin \theta \quad (2.4)$$

By substituting $\beta(\omega) = \frac{\omega}{c}$, Eq. (2.4) becomes Eq. (1.3). Eq. (1.3) means that the steering angle in delay-based control is independent of frequency. A true time delay is independent of frequency and preserves the beam pointing direction over the entire signal bandwidth.

In integrated photonics TTD can be achieved by controlling the length of a segment of waveguide or optical path. The delay caused by a waveguide length L is given by:

$$\tau = \frac{n_g L}{c} \quad (2.5)$$

Here in Eq.(2.5), n_g denotes the group index of the waveguide. The predominant contribution to the delay is that of the group's velocity, so broadband fidelity is maintained. More widely

spaced beam steering without angular distortion can also be obtained by progressively varying the path length in each of the channels [128], [129]. While TTD architectures do not suffer from beam squint, thermo-optically tuned TTDs and carrier charge injected devices are typically power consuming and difficult to scale [130], [131]. This has motivated research into non-volatile programmable delays using phase change materials (PCM). These devices are described in the following section. Details on PCM materials are described in Appendix A.1.

2.2 Optical TTD fundamentals

TTD steering of the array requires the generation of controlled delays across a number of parallel channels driving the radiating elements of a phased array. In the case of integrated photonic beamforming networks, this is done by applying an appropriate programmable variation of the effective optical path delay across the channels, to form a steadily increasing delay profile across the array [132]-[134].

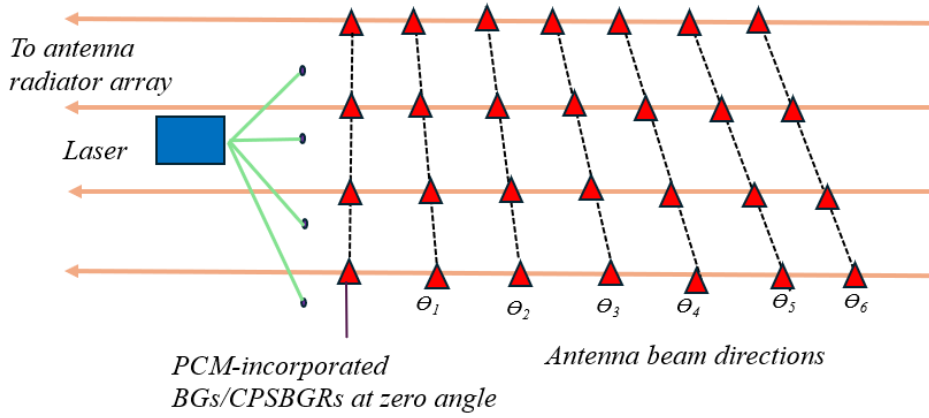


Fig.2.1. On-chip integrated optical TTD beamforming system within an antenna, which can be transformed for transmission or reception by adding circulators and waveguide circuits (modulators and amplifiers are not shown here). Programmable on/off reflectors are depicted as red triangle and optical waveguides as rust color lines.

In an optical TTD system, there are typically multiple waveguide branches fed from a common input source as shown in (Fig.2.1). Each branch contains a number of reflection or transmission

points, which are at increasing distances from the input. To apply a time delay, a particular reflection point in that branch is turned on and the optical signal forced into a defined distance before being reflected back (Fig.2.2). The time delay is given by the optical length of the path.

If L_{opt} denotes the optical path length ($n_{eff} \times \text{physical length}$), induced time delay is given by:

$$\tau = \frac{n_g L_{opt}}{c} \quad (2.6)$$

The delay difference between two adjacent radiating elements is given by

$$\Delta\tau = \frac{n_g \Delta L_{opt}}{c} \quad (2.7)$$

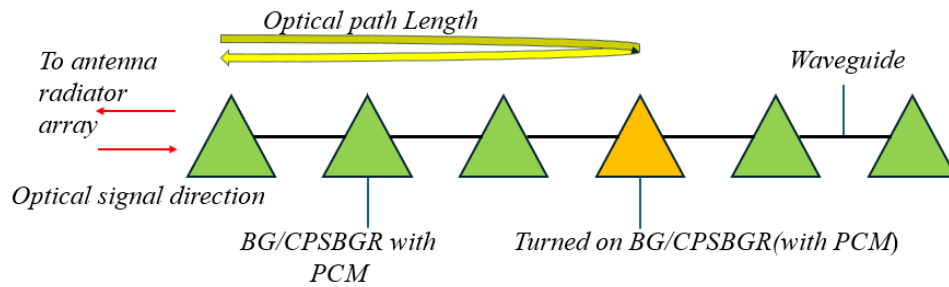


Fig.2.2. Delay line containing a series of BGs/CPSBGRs (represented as green triangles) connected by waveguides; the dark yellow triangles designate the turned-on BG/PSBGR

Here in Eq. (2.7), ΔL_{opt} denotes distance between adjacent reflections. This discrete path length programming can achieve precise time delay without the need for continuous variations in the refractive index, improving stability and scalability of the integrated platform. The relationship between delay and beam steering can be obtained by considering a linear array with inter-element spacing d . To steer the beam towards an angle θ , then for the different channels, there must be a progressive delay between each channel. Combining Eq. (2.4) and (2.6), Eq. (2.8) can be obtained.

$$\Delta L_{opt} = \frac{d \sin \theta}{n_g} \quad (2.8)$$

This Eq. (2.8) relates the required optical ΔL_{opt} to the desired steering angle and the n_g . Two scaling implications are derived from this relationship. First, there is a linear relationship between steering angle and required optical path difference. Second, by using waveguides with higher group index, the delay is compressed into a smaller physical size [135], [136].

The broadband capabilities of TTD are based on the fact time delay does not affect the steering condition. The beam is steered with the group velocity, not the phase velocity. If the dispersion of the group index is sufficiently low, then the TTD beam will steer over the entire bandwidth of the system [129], [137], [138]. This property sets TTD-based architectures apart from phase-based steering where angular deviation increases with increasing bandwidth.

Contributions to broadband performance are offset by the challenges presented by large delays on small integrated chips. Increasing optical path length increases propagation loss, device footprint, and thermal response, while conventional tuning approaches such as thermo-optic tuning require active power dissipation, limiting the scalability of devices with large arrays. These drawbacks motivated the use of programmable non-volatile elements to define the position of the reflection, described in the following section.

2.3 PCM-Based Programmable Reflector Architecture

The previous Section discussed the fundamentals behind TTD. Compact, low loss, and energy efficient switches are prerequisites of programmable delay network to implement the TTD. For common integrated photonic platforms, path-length tuning is typically achieved through thermo-optic and carrier modulation, which require constant electrical bias and are therefore not easily scalable to large PIC arrays.

To address these challenges, non-volatile PCM can be used within photonic structures to implement discrete, low-power, or even no-power active reflection states. This work investigates the geometry of on-chip, PCM-integrated Bragg-based resonant structures to

achieve the desired on-chip reconfigurable reflection points along a delay line to enable the implementation of complex, photonic topologies.

PCMs can perform reverse phase transition properties between their amorphous and crystalline states with significant change in refractive index [139]-[141]. Antimony trisulfide (Sb_2S_3) has been chosen as PCM since it has low intrinsic losses in both amorphous and crystalline states, showing a refractive index contrast of ~ 0.60 between crystalline (3.308) and amorphous (2.712) states [142]-[146]. The temperature for crystallization of Sb_2S_3 is around 573 K and the melting point (required to achieve the amorphization) is around 823 K [142], [143], [147], [148]. This index contrast allows the effective index of the guided mode to be tuned substantially when integrated with silicon waveguides.

For our work the core idea was to design a delay line which consists of several programmable on/off reflectors. Such programmable on/off reflectors are realized as PCM- incorporated BGs or CPSBGRs (cascade of phase-shifted Bragg grating resonators). Then, each delay line induces a specific delay in the reflection path according to the position of the selected on/off reflector programmed to work as a reflector. When a particular BG/CPSBGR in a delay line is turned on (changing either from crystalline to amorphous or from amorphous to crystalline, as will be specifically indicated later), a remarkable shift can be observed in the reflection/transmission spectrum of the BG/CPSBGR. Phase change from one to another of the two phases of the material causes a change of the effective index (n_{eff}) of the grating, which in turn shifts the resonance, and thus the following Bragg wavelength:

$$\lambda_B = 2n_{\text{eff}}\Lambda \quad (2.9)$$

where Λ is the grating period. A change in n_{eff} is induced by the PCM phase transition therefore results change in the λ_B . By setting up different delay lines and turning on specific programmable reflectors at different positions, desired time delays can be achieved in different delay lines. The delayed signals obtained can be utilized to modulate radio signals in an antenna radiator array [133], [149], [150]; hence, it can transform into a phased array that is able to steer the microwave beam along desired angles according to the relative delay

between consecutive delay lines. All optical components are integrated in a monolithic way to obtain high compactness and efficiency. The desired wavelength of operation (~ 1550 nm) was chosen as the Bragg resonance condition Eq. (2.9).

There are two methods to approach the architecture in Fig.2.2, meaning that the optical path selection can be achieved in two different ways, depending on the use of BGs (class I) or CPSBGRs (class II), as discussed below. In both cases, λ_0 is the operating wavelength of the laser source. The length of the waveguide between each BG/CSPBGR is non-uniformly chosen (it will be explained in detail in Programmable Delay-Line Design). The waveguide is realized as a silicon wire immersed in SiO₂ with a width of 450 nm and a height of 220 nm. The waveguide has an effective index, $n_{\text{eff}w0}$, of 2.347 and a group index, n_{wg} , of 4.272 for both configurations. A graphene microheater can be used by applying a voltage across it to heat the PCM in a few microseconds with high efficiency for both the BG and CSPBGR [151]. Through controlled heating and cooling, turning on specific BG/CSPBGRs can be performed.

Class I

In class I architecture, the TTD system was designed to work at the operating wavelength of $\lambda_0 = 1550$ nm. BGs work as programmable on-chip turned-on reflectors as the PCM changes from an amorphous state to a crystalline state.

A BG was designed in such a way that it contained two alternating sections with two different widths of 450 nm and 550 nm (W_1 and W_2 , respectively), both having a height of 220 nm (H), as shown in Fig.2.3 (a). A cross-section of a SOI PCM-coated BG with a graphene microheater is shown in Fig.2.3 (b). The period of the BG (Λ) was fixed at 306 nm to obtain a resonance wavelength of ~ 1550 nm in its crystalline phase; we chose 200 periods, which gave a total length of the BG of 61.2 μm . The height of the PCM was the same as that of H and the width (W_p) was 150 nm.

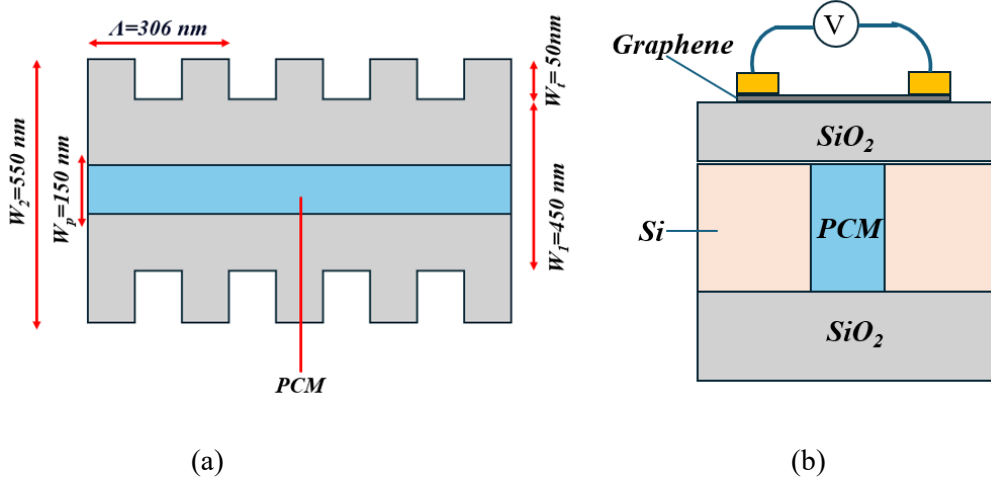


Fig.2.3 (a) Top view of SOI strip showing the geometry of one PCM-coated BG. **(b)** Cross-section of a SOI PCM-coated BG with a graphene microheater.

In this case, the reflection wavelength of the turned-off reflector (amorphous state) was 1438 nm (λ_{BA}). Instead, the reflection wavelength of the turned-on reflector (crystalline state) was λ_{BC} , which was designed to be equal to the wavelength of operation (λ_0). Primarily, when all the BGs in a delay line were in an amorphous state, no reflection was observed (Fig.2.4 (a)). When a particular BG at a specific position was turned on, the delay line showed reflection. Thus, depending on the position of the BG turned on, a specific delay was introduced into the reflected signal of the delay line (Fig.2.4 (b)). As the wavelength of operation lay in the reflection peak, this device could be named as a peak-in-reflection (or a notch-in-transmission). The thermal simulation profile corresponding with the case of the BG and the temperature as a function of time (for an applied voltage pulse of 4.5 V) are shown in Fig.2.5 (a) and (b), respectively.

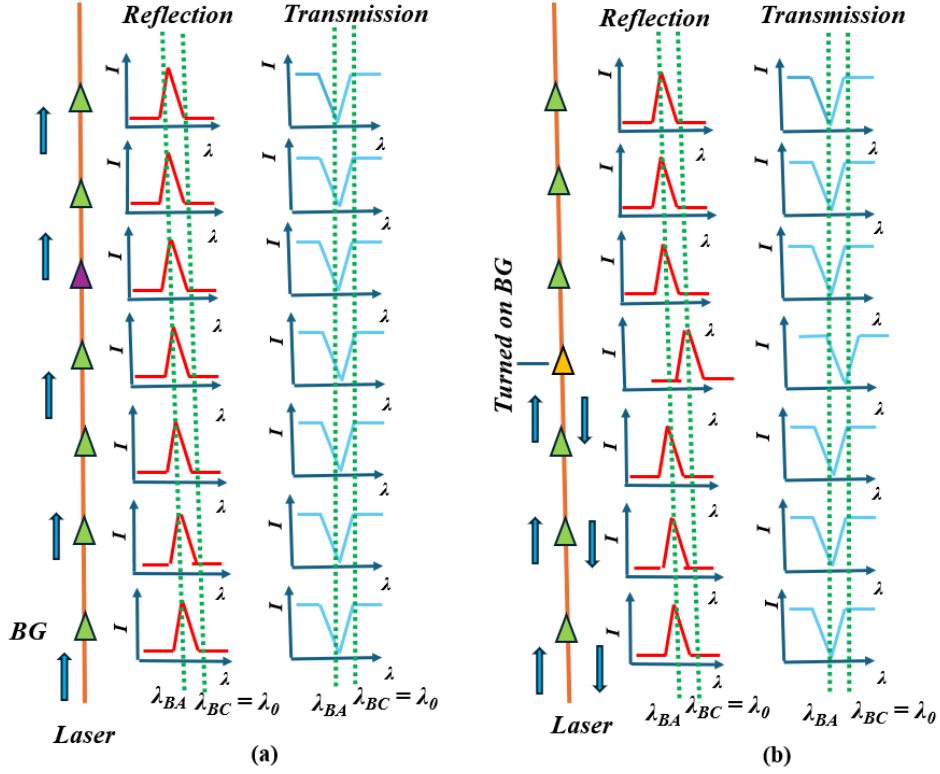
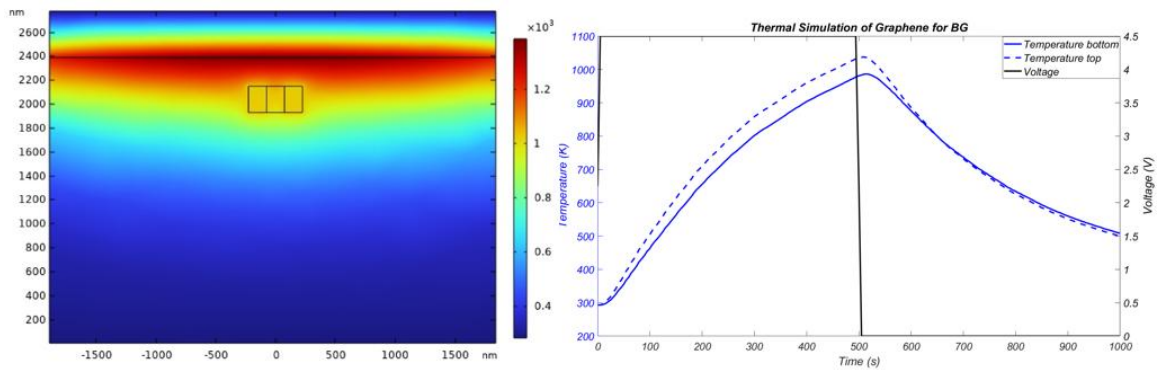


Fig.2.4. Programmable optical delay line using BGs for the selection of any one of three optical delays (as in Fig.2.9). Here, $\lambda_{BC} \sim 1550$ nm is the wavelength of operation (λ_0). (a) Initial all-amorphous ($\lambda_{BA} \sim 1438$) BG line, with corresponding R and T profiles. (b) Turning on the 4th BG (amorphous to crystalline), with a shift in the R profile and a shift in the T profile for the turned-on BG.



(a)

(b)

Fig.2.5 (a) Thermal profile (temperature in Kelvin) of the cross-section of the BG after 500 ns of a 4.5 V pulse was applied to the graphene electrodes (graphene electrodes were simulated to be 4.3 μm in length). (b) Temperature vs. time during the amorphization process evaluated at the top (dashed line) and bottom (solid line) for PCM of the BG.

Class II

In this architecture, TTD system designed to work at the operating wavelength of $\lambda_0 = 1550.6 \text{ nm}$, could also be based on the notch reflection of a CPSBGR (with the same period length as the BG). The CPSBGR was designed by adding a layer of PCM (separated by 70 nm of SiO_2) atop of a Si-based phase-shifted Bragg grating resonator (PSBGR). The CPSBGR was designed in such a way that the transmission wavelengths of the CPSBGR in a crystalline state would overlap the reflection wavelengths of the CPSBGR in an amorphous state.

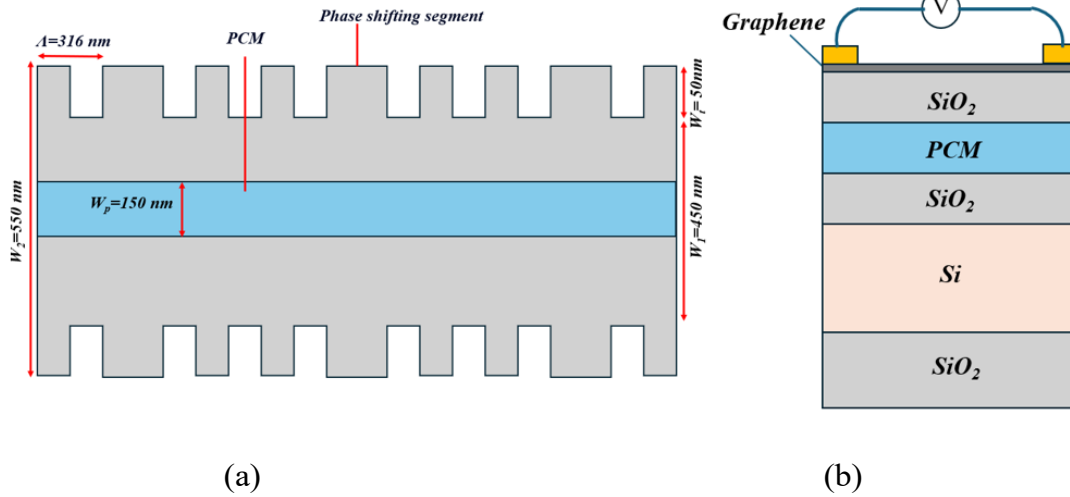


Fig.2.6 (a) Top view of SOI strip showing the geometry of one PCM-coated CSPBGR. (b) Cross-section of a SOI PCM-coated CSPBGR with a graphene microheater.

One PSBGR in the CPSBGR had almost the same dimensions as the class I BG, with a different period of 316 nm used to obtain a resonance wavelength of $\sim 1550.6 \text{ nm}$ in its crystalline phase.

The height of the PCM was set to 70 nm and the width (W_p) was 150 nm. Instead of using a single PSBGR, we opted to use a cascade of 3 PSBGRs, named CPSBGRs (Fig.2.7 (a)), and a cross-section of a SOI PCM-coated CPSBGR (including the graphene microheater) is shown in Fig.2.7 (a). The length of each phase-shifting segment was chosen to be same length as the period length, i.e., 316 nm. In the design of a CPSBGR, the structure is often synthesized as a cascade of coupled optical resonators (3 PSBGRs as mentioned above), with each phase-shifted Bragg section represented as an optical cavity, and the final structure is regarded as a realisation of a multi-stage optical filter. To achieve this response, a Butterworth filter was chosen. A Butterworth filter has the characteristic of a maximally flat transmission in the passband. The filter order equals the number of cascaded resonators. The section lengths are calculated using normalized Butterworth filter coefficients. These coefficients are then used to define the distribution of energy among the resonators. Mapping the coefficients to physical section lengths of the CPSBGR resulted in flat-top transmission with the specified bandwidth. The length of 126.4 μm was therefore determined by this synthesis approach rather than being defined arbitrarily [134], [151], [152].

Initially, all CPSBGRs were kept turned off; in class II, the turned-off state referred to keeping all CPSBGRs in a crystalline state. In the turned-off state, the CPSBGRs were designed to transmit at λ_{BC} (Fig.2.7 (a)). Under this condition, no signal was detected at the output because the operating wavelength λ_0 was λ_{BC} (~ 1550.6 nm). Shifting of the reflection notch occurred due to the change in the refractive index as the CPSBGR at a specific position was turned on (amorphous state). In this case, the notch in the reflection spectrum shifted away from λ_{BC} to λ_{BA} (1547 nm) and the CPSBGR reflected light at the operating wavelength, λ_0 (Fig.2.7 (b)).

Thus, a delay in class II was introduced by turning the CPSBGR from a crystalline to an amorphous state. The time delay depended on the position of the turned-on CPSBGR. As the wavelength of operation lay in the reflection notch, this device could be named as notch-in-reflection (or peak-in-transmission). The thermal simulation profile corresponding with the CPSBGR and the temperature as a function of time (for an applied voltage pulse of 4.5 V) are shown in Fig.2.8 (a) and (b), respectively.

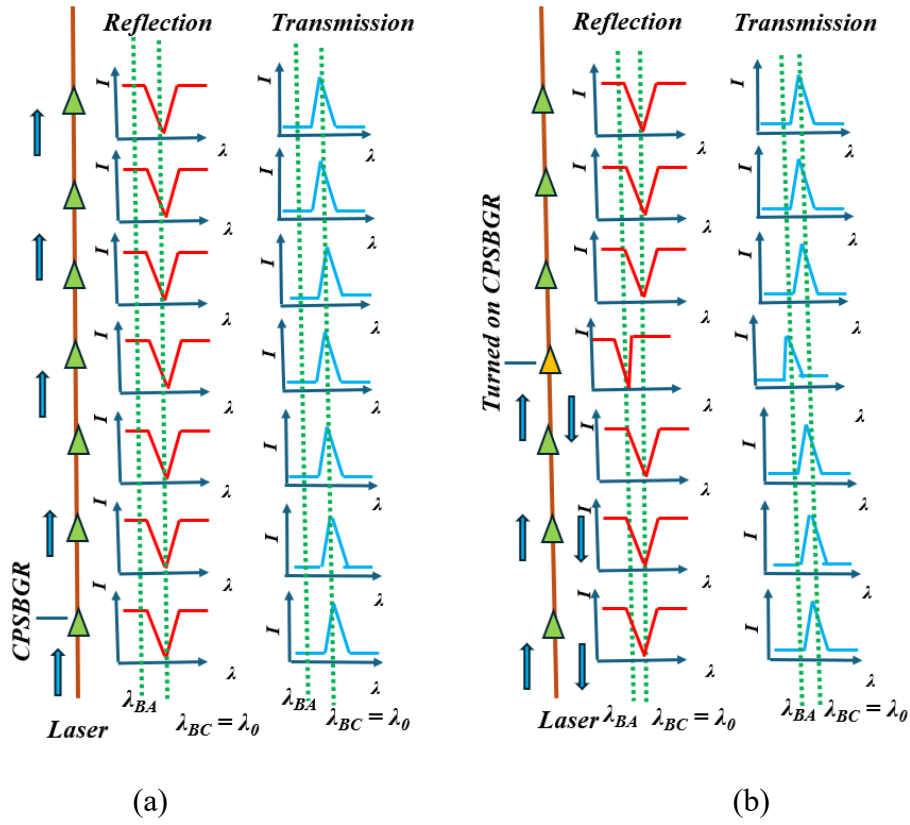


Fig.2.7 Programmable optical delay line using CPSBGRs for the selection of any one of three optical delays (as in Fig.2.9). Here, ($\lambda_{BC} \sim 1550.6$ nm) is the wavelength of operation (λ_0). (a) Initial all-crystalline ($\lambda_{BC} \sim 1550.6$ nm) CPSBGR line, with corresponding R and T profiles. (b) Turning on the 4th CPSBGR (crystalline to amorphous, i.e., $\lambda_{BC} \sim 1550.6$ nm to $\lambda_{BA} \sim 1547$ nm), with a shift in the R profile and a shift in the T profile for the turned-on CPSBGR.

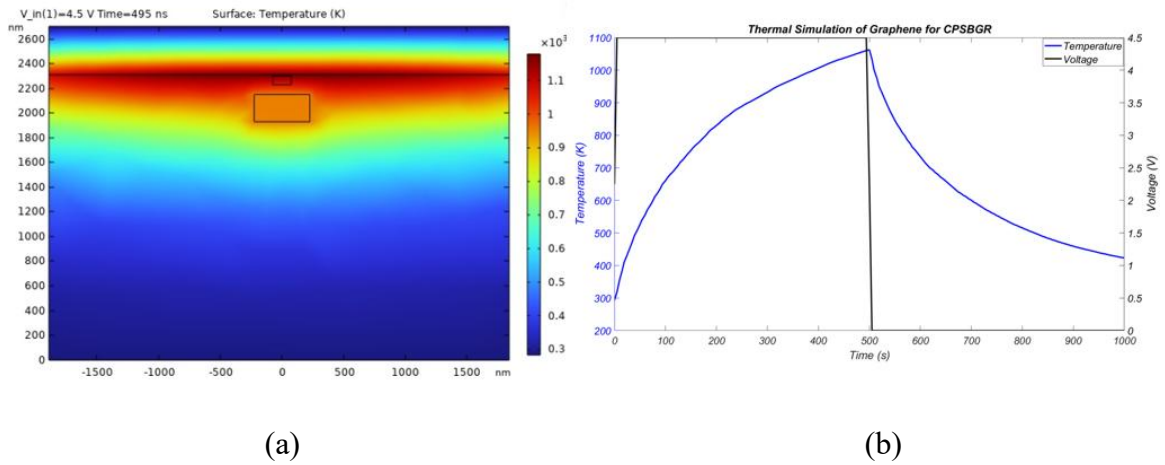


Fig.2.8. (a) Thermal profile (temperature in Kelvin) of the cross-section of the CSPBGR after 495 ns of a 4.5 V pulse was applied to the graphene electrodes (graphene electrodes were simulated to be 4.3 μm in length). (b) Temperature vs. time during the amorphization process evaluated for PCM of the CSPBGR.

2.4 Programmable Delay-Line Design

When the architecture of a programmable reflector has been created, it is necessary to identify the geometric arrangement that is needed to create the required steering angle. The antenna design is also driven by the TTD network and the relationship between the microwave frequency and steering angle, inter-element spacing and distribution of optical path-lengths. The highest microwave frequency of a linear phased array f_{max} , the required minimum increment in delay between adjacent elements to achieve a minimum steering angle θ_{min} , can be obtained from the delay-steering relation:

$$\tau_{min} = \frac{d \sin \theta_{min}}{c} \quad (2.10)$$

The minimum required optical path-length difference can be found by replacing Θ in Eq.(2.8) with Θ_{min} . To generalize the design for multiple steering angles, the distance between the reflection points in the i^{th} delay line can be written as:

$$d_{i,NL} = (NL)d_{min} \left(\frac{\tan \theta_i}{\tan \theta_{min}} \right) \quad (2.11)$$

where NL is the delay-line index, d_{min} is the minimum spacing corresponding to θ_{min} , and θ_i is the desired steering angle. The minimum spacing parameter itself is given by:

$$d_{min} = c \frac{\sin \theta_{min}}{4f_{max} n_{eff}} \quad (2.12)$$

These ratios define the non-linear, geometric progression that the programmable reflection points in the delay network will take as the desired steering angle is approached, affecting both the chip area and the total optical loss of the device.

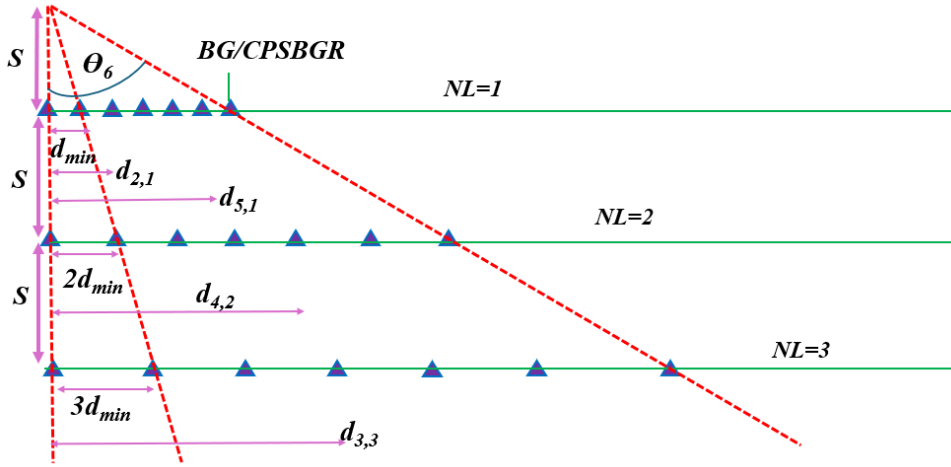


Fig.2.9. Array of delay lines with corresponding steering angles.

Eq. (2.9) indicates that the length of required path length increases as the steering angle increases, reaching its maximum when $\Theta = 90^\circ$. In practice, steering range is limited by the physical dimension of the chip and acceptable insertion loss [153]-[155].

2.5 Numerical modelling and simulation work

In this Section we have investigated an array of delay lines as sketched in Fig.2.9. Firstly, we have analyzed the spectral profile of the designed single BG and CPSBGR, as shown in Fig. 2.10 (a) and Fig. 2.11 (a), respectively. The shift along the wavelength axis was clearly visible in the spectral profile. Fig.2.10 (b) and Fig.2.11 (b) represent the phase-relation of a single BG and a single CSPBGR with the wavelength, respectively.

Subsequently, we investigated a series of delay lines with seven BGs/CPSBGRs to perform beam steering (Fig. 2.9), focusing on the X band (8 to 12 GHz) for the modulating signal. The length of the waveguide was non-uniformly chosen according to Eq.(2.11), in which NL is the delay-line number and $d_{\min}$ is the distance between the center of the first and second BG/CPSBGR along the delay line. This distance was calculated according to Eq. (2.12), in which $\Theta_{\min}$ is the minimum steering angle (designated as 8°), n_{eff} is the effective refractive index of the waveguide, $f_{\max}$ is the maximum microwave frequency in the band, and c is the speed of light in a vacuum.

The design was adapted for a few angles, Θ_i , ranging from 8° to 16° , 24° , 32° , 40° , or 48° [134]. In this work, the simulation and numerical calculations were carried out by an eigenmode expansion (EME) analysis [156] using the MODE module of Lumerical software (version 1.9.3724) [157] and the Transfer Matrix approach [158]. An integrating framework was applied for the full vectorial modelling of optical propagation in photonics structures such as BGs/CSPBGRs as well as the waveguide.

The vertical distance between the two delay lines (S) in Fig.2.9 was calculated to be 1.25 cm according to Eq. (2.13), where $\lambda_{\min}$ is the minimum microwave band wavelength for the X band (8–12 GHz).

$$S = \frac{\lambda_{\min}}{2} \quad (2.13)$$

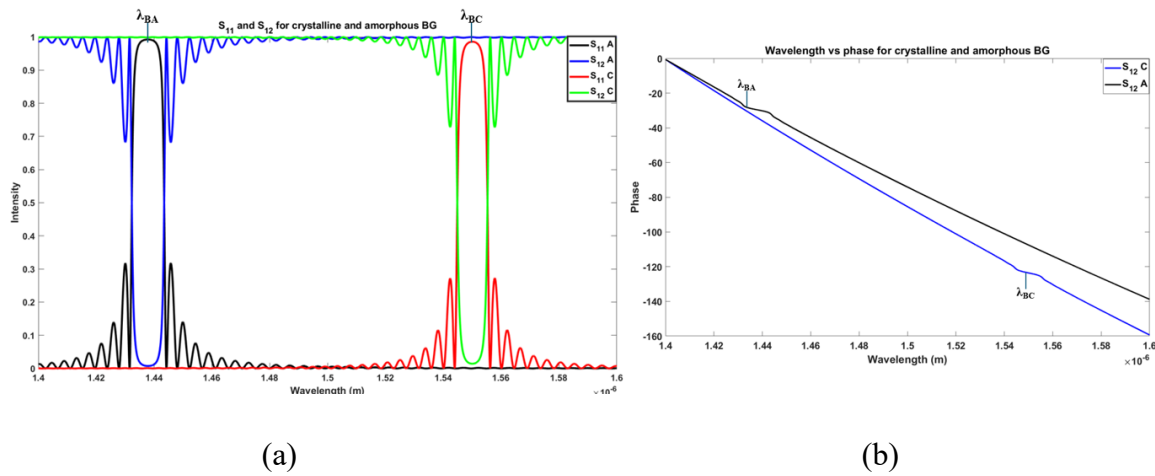


Fig.210 (a) Reflection and transmission spectral responses of PCM-coated Bragg resonator. S_{11} and S_{12} refer to reflection and transmission, respectively, in crystalline or amorphous states. (b) Phase dependence of the wavelength of a single BG plotted for transmission only.

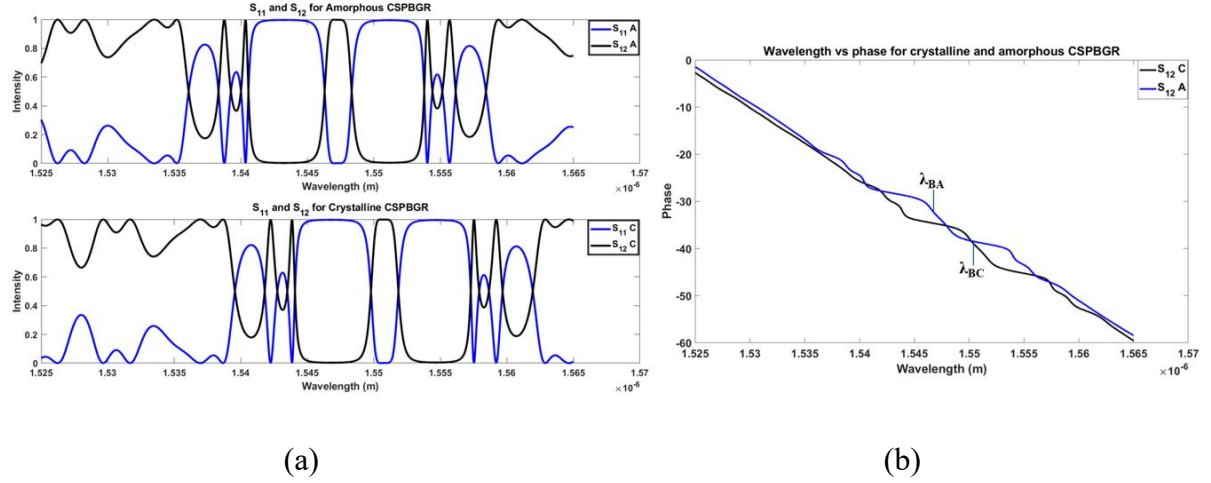


Fig. 2.11. (a) Reflection and transmission spectral response of PCM-coated CPSBGR. S_{11} and S_{12} refer to the reflection and transmission in crystalline or amorphous states, respectively. (b) Phase dependence of the wavelength of a single CPSBGR plotted for transmission only

Fig. 2.12 and Fig. 2.13 illustrate an example of the overall amplitude and phase of a designed delay line when the 4th BG and CPSBGR of first delay line was turned on, respectively.

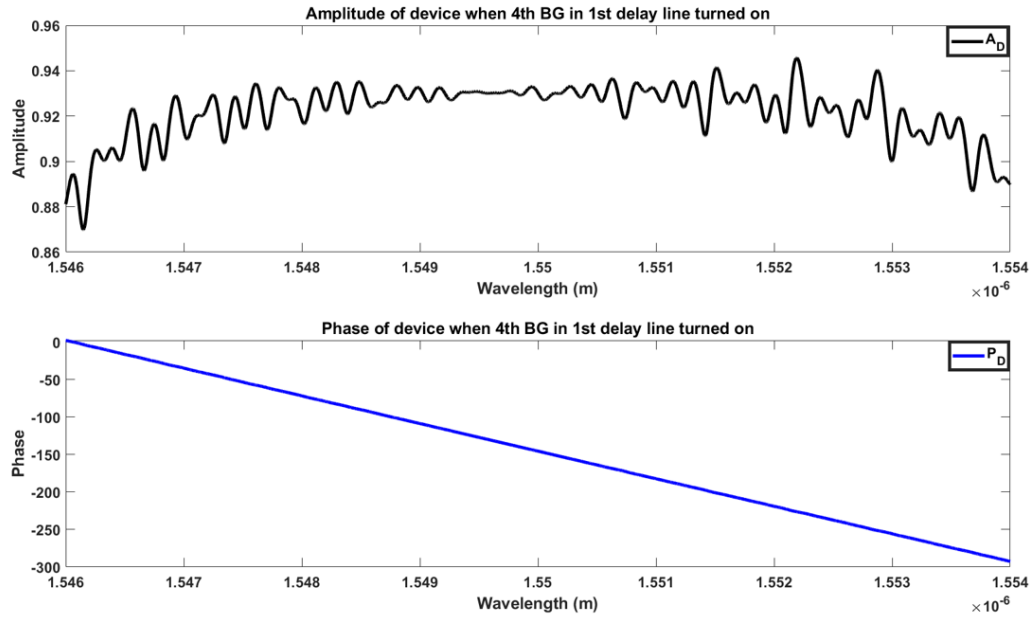


Fig.2.12. Amplitude (A_D) and phase (P_D) of the device when the 4th BG in the first delay line was turned on.

Fig.2.14 shows the different time delays induced when each BG was turned on for different delay lines and for steering at different angles such as 8°, 16°, 24°, 32°, 40°, or 48°. The maximum induced time delays (i.e., when the last BG was turned on) for each line were 83.3 ps, 166 ps, and 250 ps, respectively, and the maximum time delays induced for the CPSBGR across different delay lines were 97.9 ps, 181.6 ps, and 264.4 ps, respectively. The relative delay between different delay lines gave the desired steering angle.

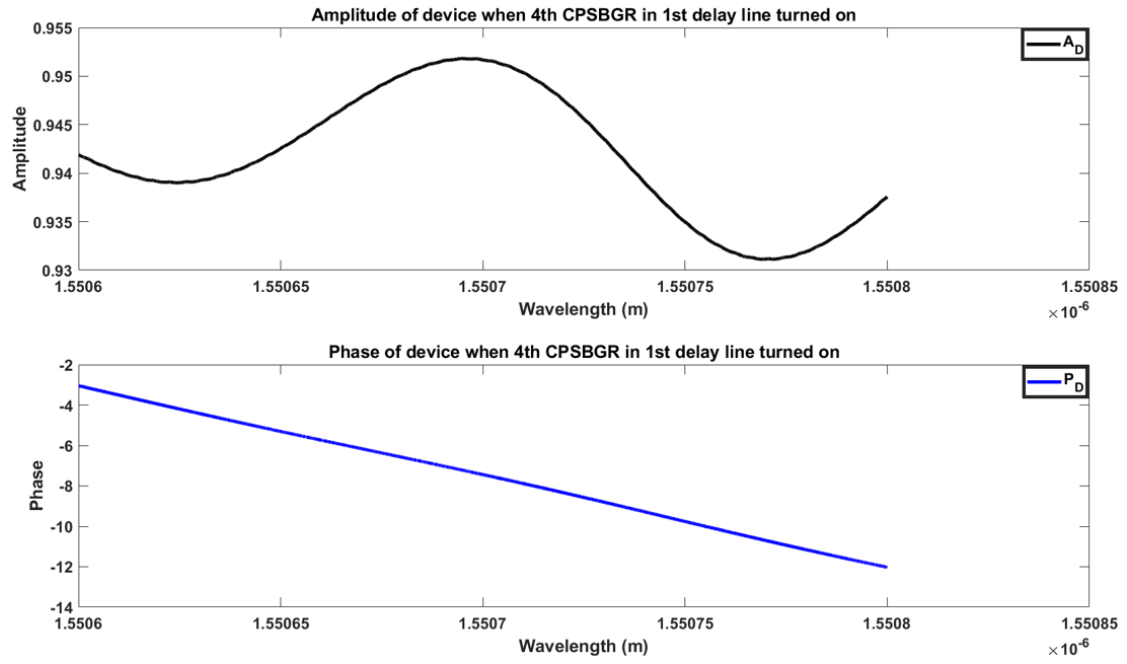


Fig.2.13. Amplitude (A_D) and phase (P_D) of the device when the 4th CPSBGR in the first delay line was turned on.

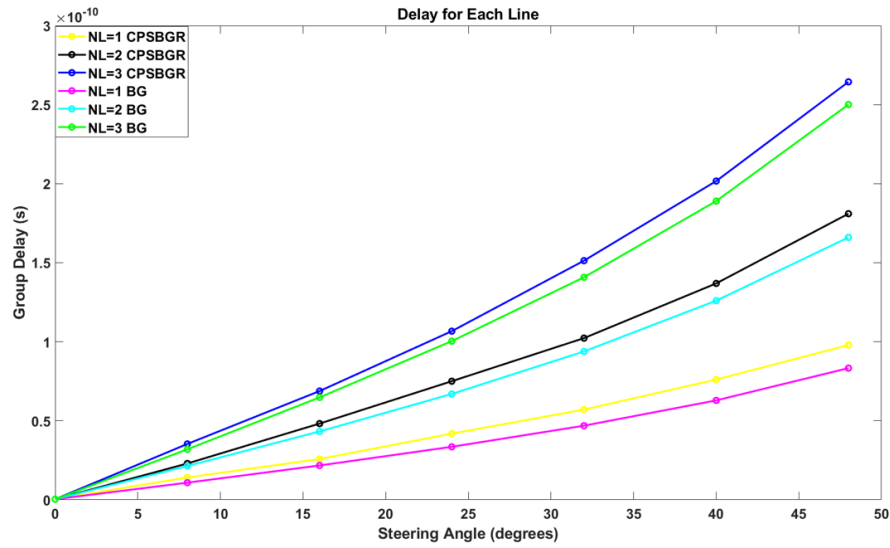


Fig.2.15. Group delay induced when each BG/CPSBGR was turned on for different steering angles and different delay lines (NL).

2.5 Chapter summary

In this chapter, the work done on delay-domain beam steering schemes based on programmable optical TTD networks and customary phase-based steering schemes are explained, discussing the existing limitations of the latter schemes due to the beam squint resulting from their intrinsic frequency dependence. By using true time delay, the angular dispersion can be removed through the frequency-independent temporal offsets. An integrated optical version using programmable delay lines on a silicon-on-insulator platform was developed based on Bragg-based resonant structures with phase change material (PCM) coatings. The PCM was used to provide discrete non-volatile states for reflection. The large refractive index contrast and low photon losses of the Sb_2S_3 PCM enabled resonance controlled switching of transmission and reflection states at telecommunication wavelengths.

A system-level modal relationship between steering angle, optical path-length difference and group index was derived, revealing fundamental trade-offs between steering range, angular resolution, device footprint and insertion loss. Numerical modelling of eigenmode expansion, transfer matrix analysis and thermal simulations confirmed operation of the programmable delay feature and broadband operation in the X-band. It has been shown that the design can achieve a high degree of beam squint suppression, discrete programmability in delay, and reduced static power consumption compared to continuous thermo-optic tuning. The time delay is thus achieved by the choice of discrete Bragg-based programmable reflectors in each delay line, where each placed reflector can be moved along the wave propagation, increasing the optical path length and delay. The reflectors of the delay lines are switched on in groups to synthesis a progressive delay distribution so that the beam can be steered at arbitrary discrete angles. Spacing between the reflectors in a delay line is an integer number of multiples of the minimum spacing, $d_{\min}$, ensuring the same angular resolution across the array. This results in digitally programmable delay states with the action of a reflector being equivalent to an on/off binary element. Collectively, the programmable reflectors provide scalable beamforming in a microwave phased-array system with non-volatile operation and lower static power consumption. The downside to delay-domain beamforming is that increased steering angle requires greater optical path difference, leading to increased propagation loss and chip area.

On the other hand, TTD provides broad bandwidth fidelity and avoids beam squint. The same scaling with complexity is obtained, in the phase domain, since there are more independent controlled pixels when the optical phased array is made up of many pixels. The architecture we describe in this chapter is dedicated to 1D beam steering, on a linear array, by distributing delays along the array. Similar delay approaches in two dimensions (2D) lead to more stringent requirements, in terms of path-length control, device area, and insertion loss.

Because the optical path-length delays stack only linearly with the number of elements, current research goes toward beam steering systems based on spatial-phase modulation only. This chapter describes our work on the one-dimensional beam steering on the silicon-on-insulator (SOI) platform using programmable TTD networks. While these delay-domain approaches reduce the effects of beam squint, they run into practical limitations for larger arrays or higher-dimensional steering.

The next chapter translates the beam steering effect from delay-domain to phase-domain. The beam steering dimensionality is then increased from 1D to 2D, and the underlying technology is translated from SOI to lithium-niobate-on-insulator (LNOI) where the strong electro-optic Pockels effect can be leveraged for phase modulation. Cascaded domain-engineered lithium-niobate implementations offer a scalable means of generating large phase gradients over macroscopic apertures, enabling large beam steering angles with reduced demands on electrical control with respect to classical delay domain implementations.

Chapter 3

Phase-Domain Beam Steering Using Optical Phased Arrays

Following the delay-domain beam steering approach discussed in Chapter 2, this chapter investigates phase-domain beam steering using optical phased arrays.

3.1 Electro-Optic Phase Modulation in Lithium Niobate on Insulator (LNOI)

In contrast to the delay-domain beamforming architecture, the phase-domain beam steering scheme is based on individually controllable optical phase modulation of each radiating element. As discussed in Chapter 2, TTD is achievable in the SOI platform by manipulating the optical path length among the radiating elements. TTD is a very accurate beam forming solution for broadband beam steering, removing the problem of wavelength dependent beam squint, but the use of distributed delay elements are impractical for large, dense arrays.

One of the primary motivations for revisiting the phase-domain beam steering approach is to gain fine spatial control of the phase over a large aperture from a different material platform such as transitioning from silicon-on-insulator (SOI) to lithium niobate on insulator (LNOI), where the linear electro-optic (Pockels) effect is many orders of magnitude stronger than what can be obtained in silicon. This allows direct, high speed and low loss optical phase modulation of each element of the optical beam without the need for variations in the geometric path length. LNOI provides a fundamentally different way to manipulate the optical phase than customary methods, and is particularly well suited to scalable 2-D optical phased arrays.

Lithium niobate (LiNbO_3) is a uniaxial anisotropic crystal widely used in integrated photonics. Its non-centrosymmetric crystal lattice allows to make use of its linear electro-optic effect. The linear dependence of the refractive index on the applied electric field leads to ultrafast and efficient phase modulation [159]-[163], which enables phase-domain beam steering with high modulation bandwidth and compact dimensions, providing capabilities complementary to

delay-domain operation. Such phase-domain beam steering is either challenging or impossible with TTD techniques alone.

In an electro-optic crystal, the index ellipsoids characterize the optical anisotropy as the function of the direction of propagation of the light. A cut through the index ellipsoid in a plane perpendicular to the direction of propagation produces an ellipse. These radii can be interpreted to correspond to refractive indices of two perpendicular components of optical field polarization. Fig 3.1 captures the essence of this idea: the ellipse in the absence of an electric field is determined by the refractive indices of the crystal. When an electric field is applied to the crystal, the index ellipsoid is distorted according to the Pockels effect, changing the principal axes of the ellipse, and thus the effective refractive indices of the optical wave. Therefore, the optical phase of the transmitted light propagating through the material has a linear dependence on the electric field via the linear dependence of the phase shift on the material's refractive index. The electro-optic effect gives rise to the phase modulation in lithium-niobate photonic devices, as well as the integrated optical modulator and optical phased array (OPA) systems.

$$\Delta\left(\frac{1}{n^2}\right) = Y_{i,j}E_j \quad (3.1)$$

In Eq. (3.1), $Y_{i,j}$ represents the coefficients of the electro-optic tensor. E_j denotes the applied electric field component. For x-cut or z-cut LNOI configurations, most often used in integrated photonics, the dominant coefficient is Y_{33} . These values can be on the order of 30 pm/V making strong phase modulation with low voltage possible [159], [161]-[164]. The induced refractive index change can be approximated as,

$$\Delta n \approx -\frac{1}{2}Yn^3E \quad (3.2)$$

Where n is the refractive index of the lithium niobate and E is the applied electric field along the relevant crystallographic direction, which allows deterministic, high-speed optical phase control while avoiding the need for thermal tuning. An optical wave propagating through an

LNOI waveguide of length L will consequently develop a phase-shift, L is given by Eq.(3.3).

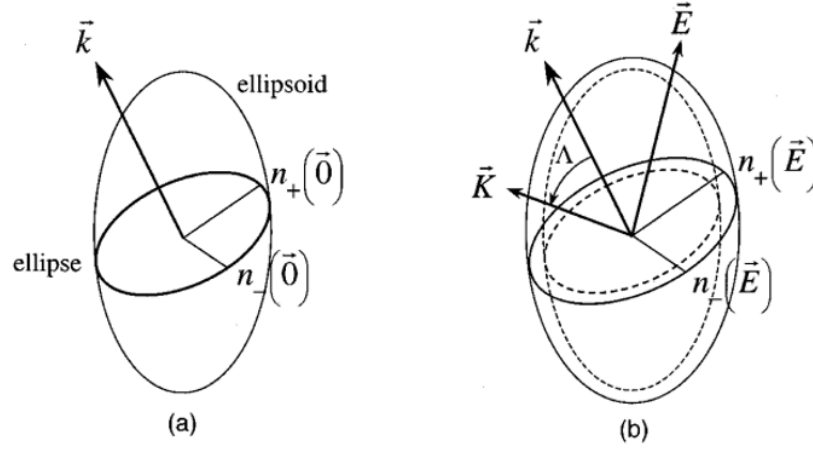


Fig.3.1 Ellipse, defined as intersection of the plane of polarization of the optical beam and the index ellipsoid, and its principal indices of refraction without (a) and with (b) an applied electric field E in the case of an anisotropic crystal [160].

$$\Delta\phi = \frac{2\pi}{\lambda} \Delta n L \quad (3.3)$$

where λ is the operating wavelength. Substituting Eq.(3.2) in Eq.(3.3) then Eq.(3.3) becomes:

$$\Delta\phi = -\frac{\pi n^3 \gamma_{33} L}{\lambda} E \quad (3.4)$$

Since the E is related to the applied voltage, V and electrode spacing d_e by $E = V/d_e$ and the d_e is the distance of separation between two electrodes, hence the phase shift can be expressed as in Eq. (3.5):

$$\Delta\phi = -\frac{\pi n^3 \gamma_{33} L}{\lambda d_e} V \quad (3.5)$$

Thus, LNOI achieves electro-optic phase modulation with a phase shift linearly proportional to both the applied voltage and the length of the interaction on a nanosecond timescale, with no static power consumption, unlike thermo-optic modulation which is slow and expensive [164]-[166].

Apart from the advantage of electro optical tuning over thermo-optic tuning in LNOI, optical wave confinement can be very well controlled in sub-micron ridge waveguides, and the optical and electric fields can be efficiently overlapped with thin-film LNOI technology. As a result, the modulation efficiency can be dramatically improved over the conventional bulk lithium niobate devices, while still maintaining the intrinsic electro-optic functionality.

An advantage of phase-domain steering is that it directly applies the spatial phase gradient onto the physical array elements. When a progressive phase shift of $\Delta\phi_n$ is applied to the n^{th} array element, the resulting steering angle is given by:

$$\beta d \sin \theta + \Delta\phi = 0 \quad (3.6)$$

In delay-domain architectures, the desired steering angle is achieved by progressively increasing the optical path-length across the aperture. In contrast, phase-domain array architectures impose the spatial phase gradient directly across the aperture. For the aperture spatial phase not scaling with steering angle, the far-field beam direction is a result of the spatial phase distribution across the array elements. This leads to fundamentally different behaviour in the scaling of aperture size when the aperture is large: for delay-domain systems this requires a proportional scaling of the physical size of the delay elements, but for phase-domain systems, an increased density of phase control is required. The requirement for the independent electrical addressing of each element quickly results in prohibitively complex interconnect architectures (as array size increases). The next sections outline a general cascade domain-engineering approach in LNOI to realize controlled phase gradients across the array

for 1D and 2D beam steering.

3.2 Structure and principle of cascaded domain engineering OPA

Conventional phase-domain optical phased arrays drive each antenna element independently with an electrical signal, allowing arbitrary spatial phase distributions to be created. However this involves complicated circuitry and more drivers as the array size increases [165], [167]-[169]. In this study rather than focusing on reducing the system complexity, we are focusing on increasing the steering angle range and the wavelength dependence of steering angle.

The cascaded domain-engineered optical phased array architecture considered in this chapter is a variant of the periodically poled lithium niobate (PPLN)-based configuration reported in [170]. In [170], the principle was demonstrated numerically using a 2D cascaded domain segmentation optical phased array, which synthesizes phase gradients in orthogonal directions. The feasibility of large-scale beam steering was investigated for a 16×16 array structure. We extended the 16×16 array structure reported [170] to 32×32 array structure which means the effective array elements is increased to 1024 from 256. It shows that the 32×32 configuration increases the steering angle compared to the 16×16 array configuration.

In the case of a cascaded domain-engineered optical phased array, the beam steering is achieved by creating a uniform phase difference between elements of the array. Beam steering condition for the main lobe is defined as:

$$\theta = \sin^{-1} \left(\frac{\Delta\phi}{2\pi} \frac{\lambda}{d} \right) \quad (3.7)$$

These expressions indicate that, for a fixed electro-optically induced phase difference $\Delta\phi$, the steering angle depends explicitly on the operating wavelength, λ .

Substituting Eq. (3.4) in Eq. (3.7), we get

$$\theta = -\frac{l_N n_e^3 \gamma E}{d} \quad (3.8)$$

The explicit cancellation of the λ term is only valid in the limit of negligible index dispersion, constant spacing between the elements independent of the wavelength, and a linear and perfectly uniform phase distribution. In fact, the effective index is wavelength dependent, and the β . It introduces a residual wavelength dependence in the synthesized phase gradient.

$$\theta(\lambda) = -\frac{l_N n^3(\lambda) \gamma E}{d_x} \quad (3.9)$$

This indicates that refractive index dispersion directly influences the angular deflection.

Apart from extending the studies done in [170], we also explored the unexplored dependence of wavelength on steering angle.

LN is chosen for cascaded domain engineering OPA, since it has broad optical transparency range (0.35-4.5 μm), electro optically tuned prominent birefringence and high electro optic activity (31.45 pm/V). LN has ordinary and extraordinary refractive indices 2.138 (n_o) and 2.214 (n_e), respectively [159], [161]-[163], [171], [172].

Before dwelling into how cascaded periodically poled LN electro-optical phased array can achieve 2D beam steering, it is needed to understand how 1D beam steering is achieved. We highlight that this study focuses on the principle that each domain of the cross section is treated independently.

The cascaded periodically poled optical LN phased array is a multi-layer structure created through domain engineering inside the LN, electro-optical crystal. This domain engineered structure enables uniform phase difference between adjacent array elements (i.e. ferroelectric domains) when the beam exits the crystal. Fig. 3.2 shows the four-layer cascaded periodically poled electro-optical phased arrays. Length (l_i) and width (d_i) of each ferroelectric domain decreased by half with each successive layer, along x and y axis, respectively. The electro-

optic phase shift induced in each ferroelectric domain also decreases accordingly, i.e. is reduced by half in each successive layer. The phase shift in positive ferroelectric domain is $\Delta\phi_+$ ($\Delta\phi_+ = 2\pi l_i \Delta n / \lambda$ and $\Delta n = -n_e^3 Y_{33} E_z / 2$) and in negative ferroelectric domain is $\Delta\phi_-$ and when it comes to $\Delta\phi_-$, the sign of Δn is just reversed.

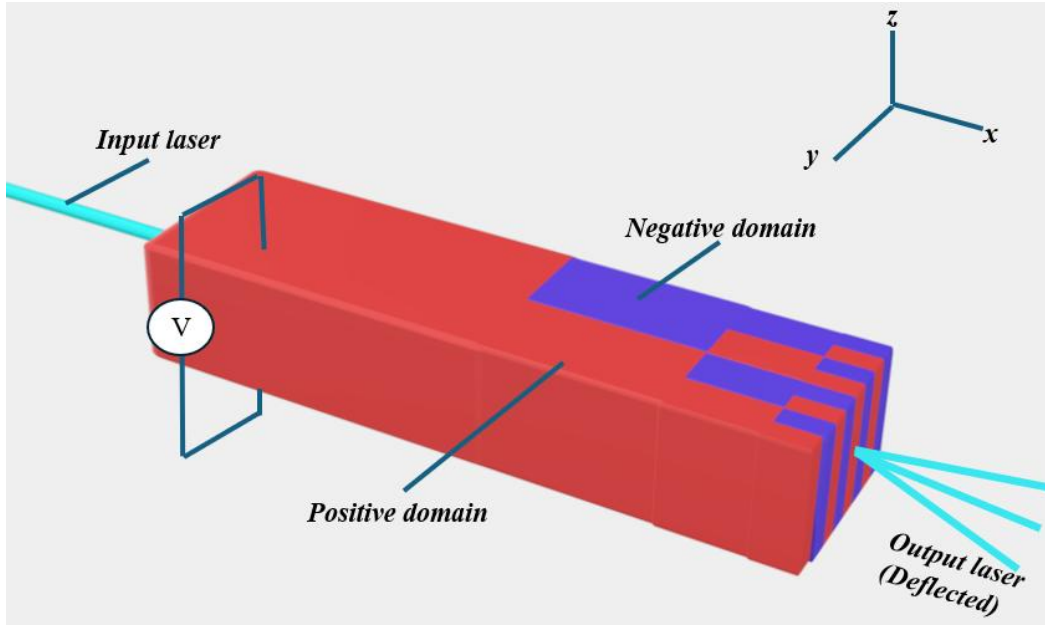


Fig.3.2 Four-layer cascaded periodically poled electro-optical LN phased array for one dimension beam steering in Y direction with just one electrode.

Here E_z is the applied electric field, Y_{33} is the Pockels coefficient. The phase shift induced by one ferroelectric domain in the last layer of four cascaded layer $\Delta\phi_4 = 2\pi l_4 \Delta n / \lambda$ and there will be 8 array elements (if there is 'N' cascaded layers, then there will be 2^{N-1} array elements, in the last cascaded layer in Fig.3.2, $N=4$). The phase difference between adjacent array elements in the last cascaded layer is $2\Delta\phi_4$. The deflection angle can be expressed according to OPA theory $\Theta_s = \lambda \Delta\phi / 2d$, where d is the width of single array element. This points out that beam steering can be achieved by a single electric field by implementing phase shift. Here, horizontal beam steering is attainable with electric field from the z direction applied to LN (Fig.3.2). Vertical beam steering is obtained by rotating Four-layer cascaded periodically poled electro-optical LN phased array in Fig.3.2 of 90° along the optical propagation axis. By combining

horizontal and vertical phased arrays two dimensional beam steering can be obtained as in Fig.3.3. In Fig.3.3 a second local reference frame has been added (x',y',z') to analyse the optical phase shift in the second LN phased array and a global reference frame (X,Y,Z) has been also introduced. The optical axis of the LN crystal is oriented along z and z' , in the first and in the second LN phased array, respectively. Phase gradient in horizontal and vertical are shown in Fig.3.4.

In this two-dimensional configuration, phase distributions of the light at the exit surface of the structure are divided into 8×8 regions, as in a two-dimensional optical phased array with 8×8 array elements. Assuming phase difference between two adjacent array elements (ferroelectric domain) in both horizontal and vertical directions are same $2\Delta\phi_4$. It can be noted that the phase gradient rises diagonally with a phase difference of $4\Delta\phi_4$ (Fig.3.5). The electro-optically induced phase shift is given by an electric field applied along the optical axis of LN crystal (so in the z and z' axes, in the first and second LN phased array, respectively).

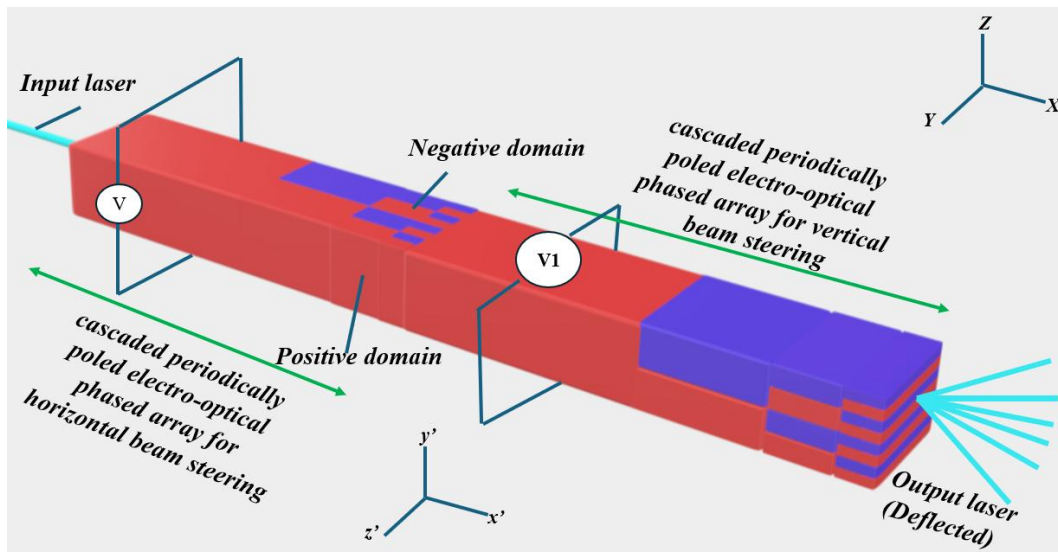


Fig.3.3 Double four-layer cascaded periodically poled electro optical LN phased array for two-dimensional beam steering by applying a pair of electric fields.

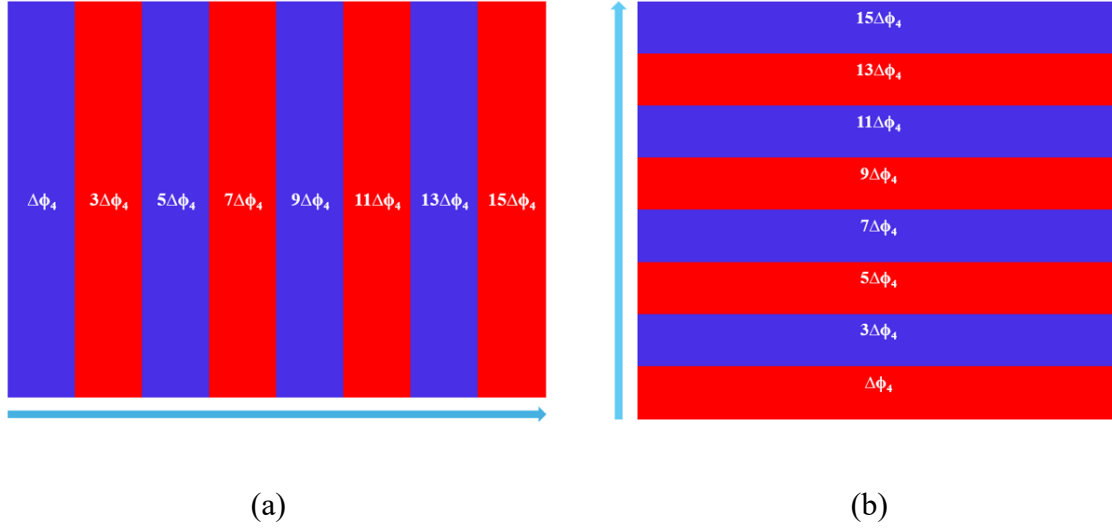


Fig.3.4 Schematic of phase gradients in (a) horizontal direction; (b) vertical direction.

The refractive indices along the X, Y, and Z axes after the application of an electric field are given by:

$$\begin{aligned}
 n_x &= n_y = n_o - \frac{1}{2} \gamma_{33} n_o^3 E_z \\
 n_z &= n_e - \frac{1}{2} \gamma_{33} n_e^3 E_z
 \end{aligned}
 \tag{3.10}$$

In Eq. (3.10), the electric field E_z is applied for Y and Z directional beam steering and γ_{33} and γ_{13} are the Pockels effect coefficients. The incident laser beam, with its polarization direction parallel to the Z axis, interacts with the first cascaded periodically poled structure. The electro-optically induced phase shift in this structure is determined by $\Delta\phi_y = 2\pi l \Delta n / \lambda$, where $\Delta n = \gamma_{33} n_e^3 E_z$. The incident laser beam, with its polarization direction perpendicular to the Y axis, interacts with the second cascaded periodically poled structure. and the electro-optically induced phase shift is determined by: $\Delta\phi_z = 2\pi l \Delta n / \lambda$ where $\Delta n = \gamma_{13} n_o^3 E_z$ along Z direction.



Fig.3.5 Schematic of phase gradients in horizontal and vertical direction.

Let us consider double N-layer cascaded periodically poled electro-optical LN phased array, where E_z and E_z' are the two electric fields applied for beam steering in Y and Z direction, respectively. The length and width of last cascade layer for beam steering in Y and Z directions are l_{Ny} , d_{Ny} and l_{Nz} , d_{Nz} . while $\Delta\phi_y$ and $\Delta\phi_y'$ are the phase differences between adjacent array elements in both directions, which can be expressed as:

$$\Delta\phi_Y = \Delta\phi_y = 2\Delta\phi_N^Y = \frac{-2\pi l_N^Y \gamma_{33} n_o^3 E_z}{\lambda} \quad (3.11)$$

$$\Delta\phi_Z = \Delta\phi_z = 2\Delta\phi_N^Z = \frac{-2\pi l_N^Z \gamma_{13} n_e^3 E_z'}{\lambda}$$

Here in Eq. (3.11), $\Delta\phi_N^Y$ and $\Delta\phi_N^Z$ are the phase shifts caused by a single ferroelectric domain in the last cascade layer of two N-layer cascaded periodically poled electro-optical LN phased array for beam steering in Y and Z direction, respectively. Moreover, γ_{33} (31.45 pm/V) and

Υ_{13} (10.12 pm/V) are the Pockels effect coefficients [169].

Deflection angle of the main lobe in Y and Z direction can be determined by:

$$\theta_{Y,\text{main}} = \theta_{y,\text{main}} = \sin^{-1} \left(\frac{-l_N^y \gamma_{33} n_e^3 E_z}{d_N^y} \right) \quad (3.12)$$

$$\theta_{Z,\text{main}} = \theta_{y',\text{main}} = \sin^{-1} \left(\frac{-l_N^z \gamma_{13} n_o^3 E_z'}{d_N^y} \right)$$

Beam steering can be controlled by manipulating two independent electric fields. Impact of cascaded periodically poled LN sequences on phase control and scanning capability of OPA can be clearly demonstrated by Eq. (3.11) and Eq. (3.12), respectively.

3.3 Numerical Results

In this Section we demonstrate one-dimensional beam steering with 32 phased array elements at the end face in Y direction, i.e. by arranging a cascaded periodically poled LN, having six cascaded layers for wavelength 1.55 μm . The length and width of the last cascaded layer, i.e. l^6 and d^6 , are 250 μm and 0.5 μm , respectively.

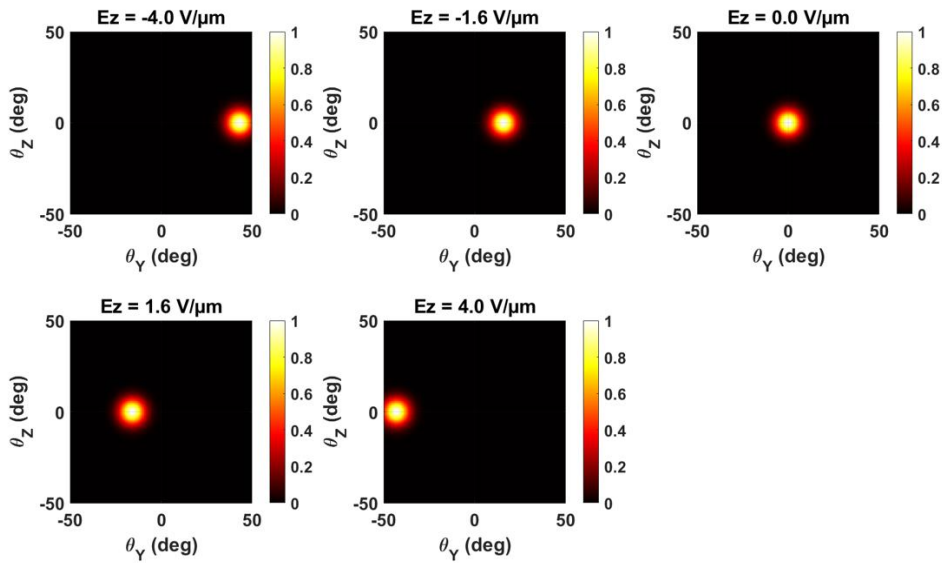


Fig.3.6 Simulated beam steering along Y axis by only applying E_z

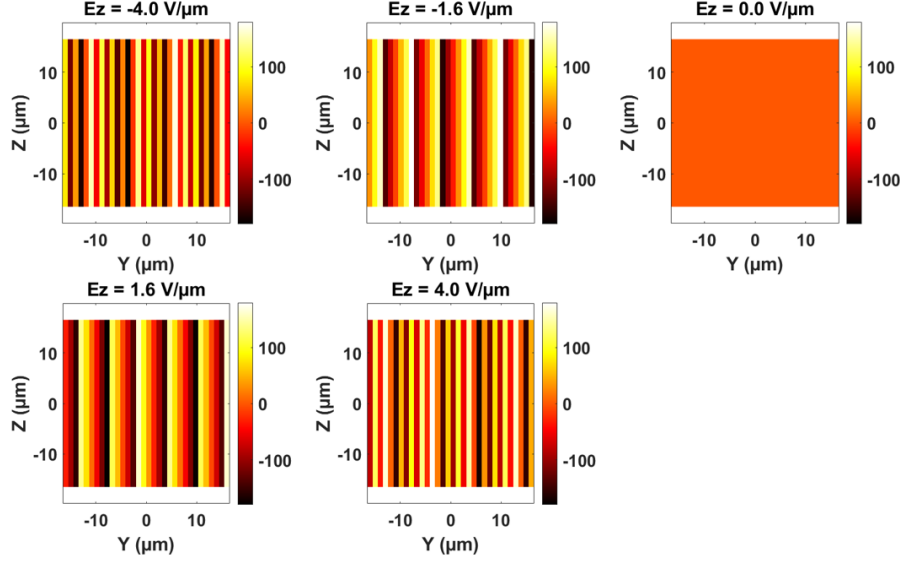


Fig.3.7. Phase distributions at the end face of one-dimensional electro-optical phased array while simulating beam steering along Y axis by applying E_z only.

Fig.3.6 shows the simulation results of one-dimensional beam steering obtained along Y direction by the application of electric fields E_z . E_z is achieved by the application of voltages -64V ($-4\text{V}/\mu\text{m}$), -25.6V ($-1.6\text{V}/\mu\text{m}$), 0V ($0\text{V}/\mu\text{m}$), 25.6V ($1.6\text{V}/\mu\text{m}$), and 64V ($4\text{V}/\mu\text{m}$), being the corresponding deflection angles -43.0493° , -15.8459° , 0° , 15.8459° , and 43.0493° , respectively. Fig.3.7 depicts the phase distributions at the end face of a one-dimensional electro-optical phased array, corresponding to the deflection angles. We estimated the intensity in Fig.3.6 by considering a Gaussian beam with a standard deviation of 5° .

Beam steering in the Z direction is achieved by arranging a cascaded periodically poled LN , having six cascaded layers as mentioned above with same dimensions but rotating the structure in fig.1 of 90° along the X axis, as already said. Here a different electric field E_z' having values -160V ($-10\text{V}/\mu\text{m}$), -64V ($-4\text{V}/\mu\text{m}$), 0V ($0\text{V}/\mu\text{m}$), 64V ($4\text{V}/\mu\text{m}$), and 160V ($10\text{V}/\mu\text{m}$), is applied. Pockels effect coefficient Υ_{13} is used for inducing electro-optic effect in z direction. Deflected angles obtained for each values of E_z' are -29.6373° , -11.4085° , 0° , 11.4085° , and 29.6373° , respectively. Beam steering and corresponding phase distributions are sketched in

Fig.3.8 and Fig.3.9, respectively.

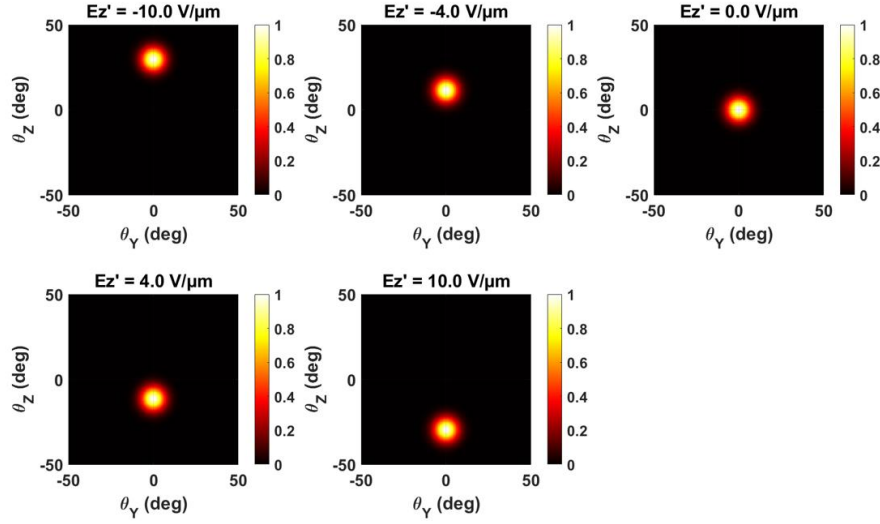


Fig.3.8 Simulated beam steering along Z axis by only applying E_z' .

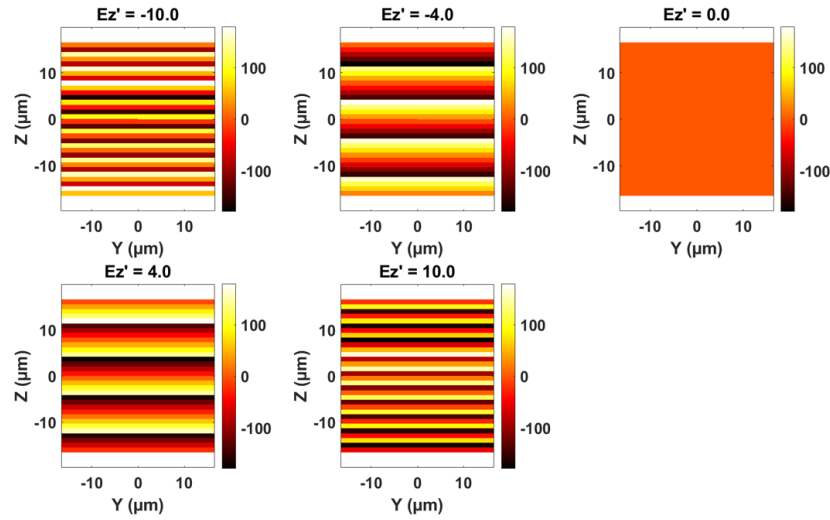


Fig.3.9 Phase distributions at the end face of one-dimensional electro-optical phased array while simulating beam steering along Z axis by applying E_z' only.

Two-dimensional beam-steering using a 32×32 phased array can be obtained by placing two cascaded periodically poled LN with six cascaded layers (arrangement is the same as in Fig.3.3.

but since here we have 6 cascaded layers, in the last cascaded layer there will be 32 phased array elements instead of 8). The length and width of each six cascaded layers are kept the same as mentioned above for the one-dimensional beam steering. Here we have applied E_z and E_z' for beam steering in Y and Z direction, respectively. Fig. 3.10 and Fig. 3.11 depict the deflection angles and the corresponding phase distributions at the end face of this two-dimensional electro-optical phased array, corresponding to the deflection angles.

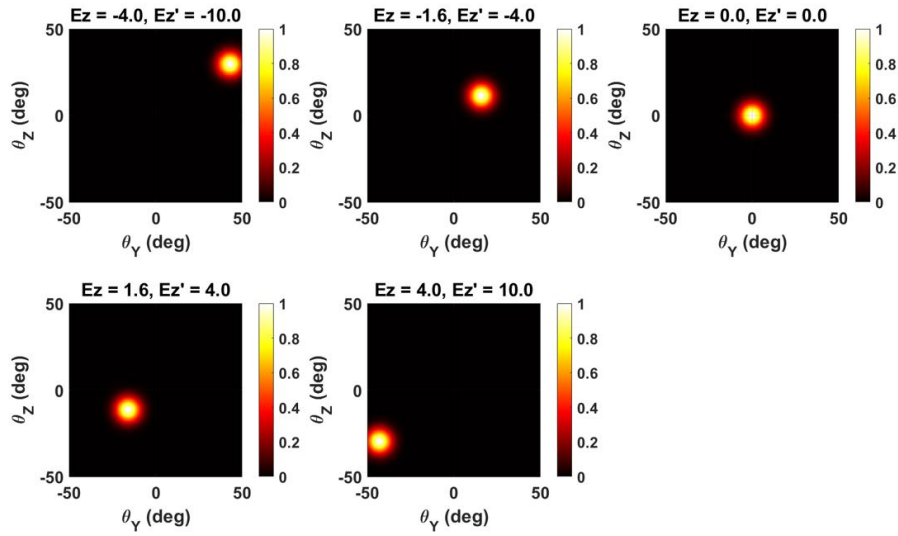


Fig.3.10 Simulated 2D beam steering along planar diagonal direction by simultaneously applying electric fields E_z and E_z' simultaneously.

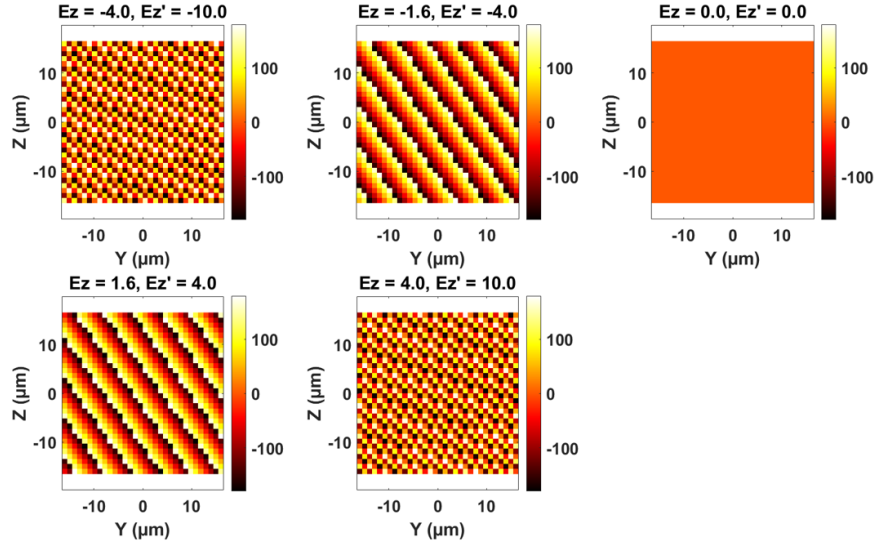


Fig.3.11 Phase distributions at the end face of 2D electro-optical phased array while applying both E_z and E_z' simultaneously.

The electro-optical phase shifts in the Y and Z directions are $\Delta\phi_Y = \pm 0.2173\pi$ and $\Delta\phi_Z = \pm 0.1574\pi$ and thereby the limiting corresponding steering angles $\Theta_Y = \pm 43^\circ$ and $\Theta_Z = \pm 29^\circ$, which enables continuous beam steering.

As a next step sinusoidal electric fields are applied, as shown in Fig.3.12. $E_z(t)$ and $E_z'(t)$ are applied for beam steering in Y and Z direction, respectively. Beam steering pattern and corresponding phase distributions are shown in Fig.3.13 and Fig.3.14. It is evident that the beam trajectory resembles circular characteristics, resembling one of Lissajous laser scanning patterns [172], [173].

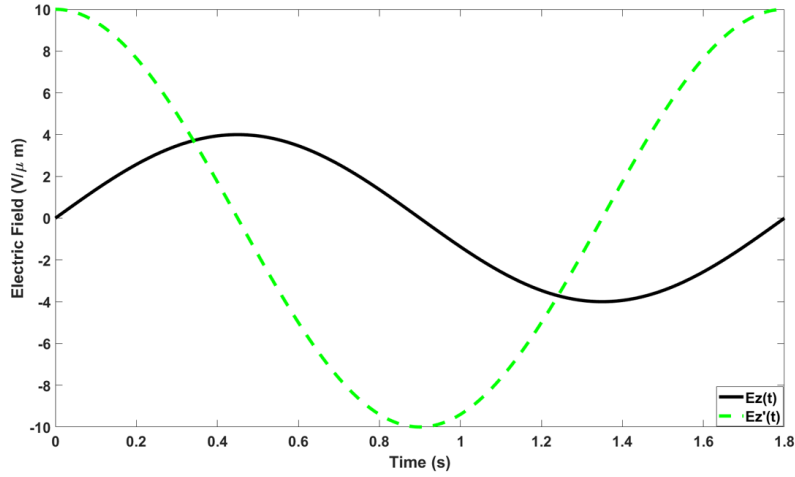


Fig.3.12 The applied sinusoidal electric field $E_z(t)$ and $E_z'(t)$, respectively.

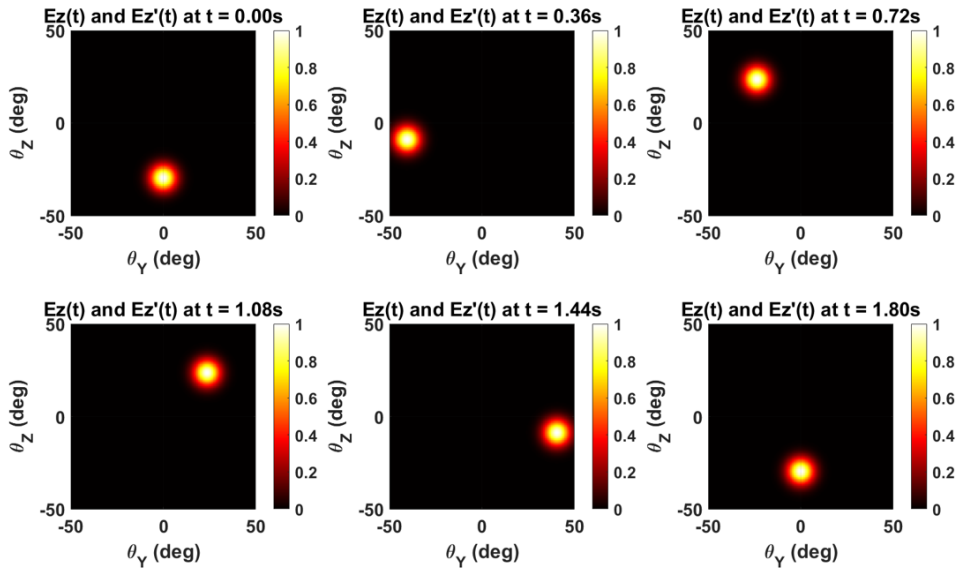


Fig.3.13 The simulated two-dimensional beam steering with the path resembles a circle when $E_z(t)$ and $E_z'(t)$ is applied along Y and Z direction.

From Eq. (3.12), it initially appears that the deflection angle is wavelength independent since the simplified formula of deflection angle does not contain any wavelength term. However, in principle the deflection angle is indeed wavelength dependent. This is due to the dispersion of ordinary and extraordinary refractive indices of LN, which was initially neglected while

simplifying the formula of deflection angle in Eq.(3.12). Hence, verification of impact of wavelength on the deflection angle and thereby beam steering has been carried out through numerical simulations. To this aim we chose cascaded periodically poled LN electro-optical phased array with dimensions $l_6 = 3000\mu\text{m}$ and $d_6 = 2\mu\text{m}$ for beam steering in Y direction. An applied electric field, E_z of $20\text{ V}/\mu\text{m}$ is used for simulation. The simulation results are shown in Fig.3.15 and the corresponding deflection angles are listed in Table 1.

Table 3.1 Wavelengths and corresponding deflection angles.

Wavelength (μm)	Deflection angle ($^\circ$)
1.54	1.24
1.55	4.84
1.56	8.53
1.57	12.25

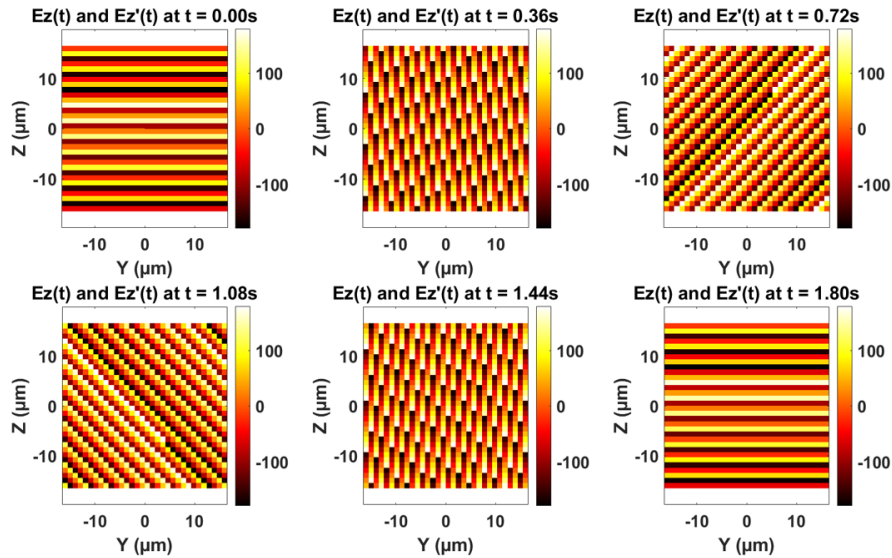


Fig.3.14 Phase distributions at the end face of two-dimensional electro optical phased array corresponding to the steering angle with the path resembles a circle when $E_z(t)$ and $E'_z(t)$ are applied.

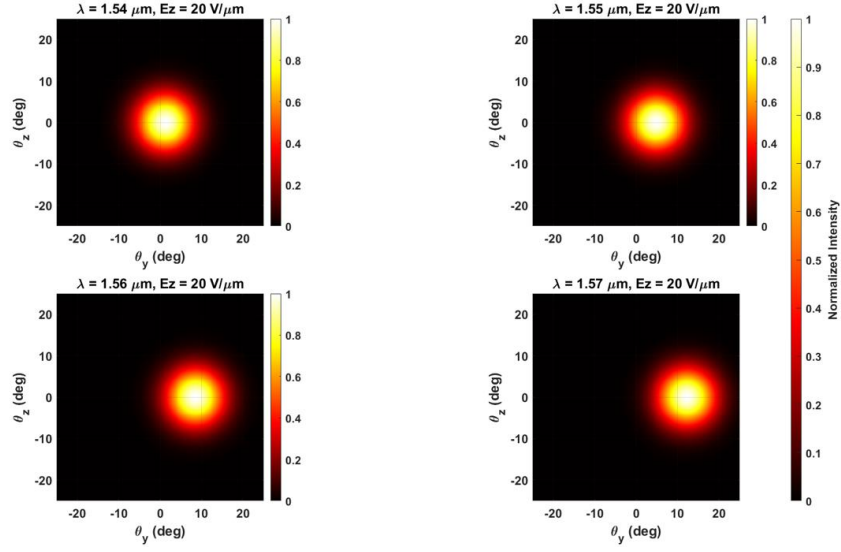


Fig.3.15 Wavelength dependence of deflection angle simulated for 1D beam steering for different wavelengths by applying a voltage of E_z .

This work suggests future research directions, including deeper theoretical modelling to incorporate wavelength dispersion as well as experimental verification for different wavelength ranges.

3.4 Chapter summary

This chapter discusses two-dimensional phase-domain beam steering based on cascaded domain-engineered LNOI architectures. In LNOI, the electro-optic Pockels effect is the physical mechanism for direct voltage-controlled phase modulation. Differently from delay-domain approaches, which create steering by adjusting optical path lengths, phase-domain techniques generate a spatial phase gradient across the aperture in order to steer the beam without using temporal delays.

This chapter describes a two-dimensional cascaded domain engineered optical phased array based on the periodically poled LiNbO₃ optical phased array reported in [170], where a 16x16 array configuration was numerically demonstrated and beam steering range, beam divergence and efficiency were characterized. In the present paper, we extend the antenna architecture to a 32x32 array and study the effects of aperture scaling and angular resolution. Our simulations

show that increasing the number of cascaded domain layers does reduce the beam divergence as expected from the array theory.

The influence of the wavelength dependency of the steering angle was also considered, both analytically and numerically. Results show that angular dispersion due to refractive index variation is rather weak for narrowband laser operation. However, since this wavelength sensitivity is not dominant in practical single-wavelength systems, we will not analyse beam quality or steering range in this chapter, having been studied in great detail in [170]. Therefore, the goal is to validate the scalability and the spectral robustness rather than to reproduce the results in previous works.

While one-dimensional beam steering with true time delay (TTD) networks was discussed in Chapter 2 on the silicon-on-insulator (SOI) platform to eliminate frequency-dependent beam squint for delay-domain systems, this chapter will discuss two-dimensional beam steering in the phase domain on the LNOI platform by cascading electro-optic phase-gradient synthesis (EPGS) unit cells in both dimensions. Together, these chapters illustrate two methodologies for beam steering: temporal delay control in SOI and spatial phase control in LNOI. The radiating antenna structure, as a coupler of guided to free space light is an important contributor to practical free space beam steering performance especially in SOI-based PIC devices. Beam performance parameters such as quality, divergence and spectral bandwidth are strongly dependent on the radiation structure. These parameters will probably require investigation of alternative radiation engineering approaches along with steering control to achieve broadband, wavelength tolerant beam steering.

Chapter 4 shows the design and characterization of chirped grating coupler antennas for broadband beam shaping and 2D beamforming on the SOI platform. Grating pitch variation along the antenna provides improved spectral bandwidth and out-of-band suppression, complementing the beam steering techniques introduced in Chapters 2 and 3. The progress from SOI delay domain control to LNOI phase domain steering and broadband antenna implementations in SOI outlines a path to integrated photonic beam steering systems across multiple platforms and control models.

Chapter 4

Radiation-Domain Beam Steering Using Chirped Grating Antenna Engineering

In addition to the delay-domain and phase-domain methods, radiation engineering of optical antennas can also be used to control the beam direction.

4.1 Grating Coupler as antenna

Grating couplers (GCs) operated as antennas have shown potential for beam forming and beam steering applications in free-space. Their planar form factor, compatibility with CMOS technology, and ability to couple guided optical modes to free-space beams make them enablers for OPA architectures to achieve beam steering via a simultaneous modulation of the phase across many emitters [175]-[177]. In 2D beam steering, the phase of several parallel emitters is controlled to steer the beam in one orthogonal axis and the wavelength dependence of the grating emission angle is used to steer it in the second.

Typical antennas based on GCs employ a constant grating period and are most efficient at a single design wavelength. Their radiation amplitude quickly decays for wavelengths below and above the design wavelength [177]-[180]. This leads to lower radiation efficiency, distortion of the main beam, increased sidelobes, and beam broadening, so that uniform-period GC antennas are not suitable for broadband applications or for wavelength-dependent beam steering schemes, which are important in modern free-space optical communication systems.

While GCs enable 2D beam steering through phase control and wavelength-dependent emission, the reliance on wavelength tuning for steering in one direction introduces an inherent bandwidth limitation, because of the strong dependence of the emission angle on wavelength, making this a persistent challenge that is not fundamentally resolved in conventional designs [168], [181], [182], [183].

Another implementation of this principle occurs in the design of the gratings themselves, for example, by employing a so-called chirped period (the grating pitch or duty cycle or both varies along the length of device) [184]-[186]. Chirped grating coupler antennas relax the phase matching condition of GCs, and allow radiation over a broad spectral range. Without due care in optimizing the chirp profile, conventional chirped designs may exhibit degrading effects including poorer beam quality, larger sidelobes, and less optimal spatial localization [176], [187]-[192].

Despite these advances, optimization procedures for chirped grating design, bandwidth optimization, beam quality analysis and multi-element beam steering, in particular for the system composed of optimized chirped grating coupler antennas with parallel configurations to achieve broadband 2D beam steering, have not been systematically demonstrated so far.

In this paper, chirped pitch grating coupler antenna (CGA) arrays in which the grating pitch varies in the propagation direction are designed. We compared the case of a CGA to a uniform-pitch GC antenna (UGA) with the same average grating period, to isolate different grating bandwidth enhancement mechanisms. The far field intensity is used together with a definition of an effective range of an operational bandwidth which adheres to the retention of beam quality. The dependence of the bandwidth and beam quality on chirp increment is considered next with the optimal chirp increment that improves the bandwidth while maintaining the beam quality identified. This optimized CGA incorporated within a phased-array configuration for beam steering in the y-direction, which is controlled by changing the phase. To overcome the problem of wavelength dependence for beam steering, we propose a 2D matrix of chirped antennas with varying average grating pitch for an array in the x-direction. In the x-axis, beam steering can be achieved through the structural tuning of the antenna architecture properties, which are independent of wavelength. This hybrid phase- and structurally engineered beam steering mechanism offers a scalable solution for broadband 2D beam steering with improved beam stability and performance compared to the customary uniform pitch grating-based architectures.

This work provides design rules for chirped grating coupler antennas and suggests that they are a viable, scalable and broadband solution for integrated photonic beam steering systems.

4.2 Design of Uniform and Chirped Grating Coupler Antennas

In this work the grating coupler antenna (GCA) has been realized on SOI platform. Each antenna element consists of an input waveguide to couple the light into the grating region and then it radiates the guided optical mode into free space. Grating is the periodic perturbation in the core of waveguide characterized by the properties duty cycle, grating period (Λ) and etch depth of the grating teeth [178], [179]. Here the GC used to couple the light in free space, hence act as an antenna. For this application beam quality, radiation efficiency, and invariance of the radiation direction to the change in wavelength etc. must be taken into account for optimal performance of the GCA.

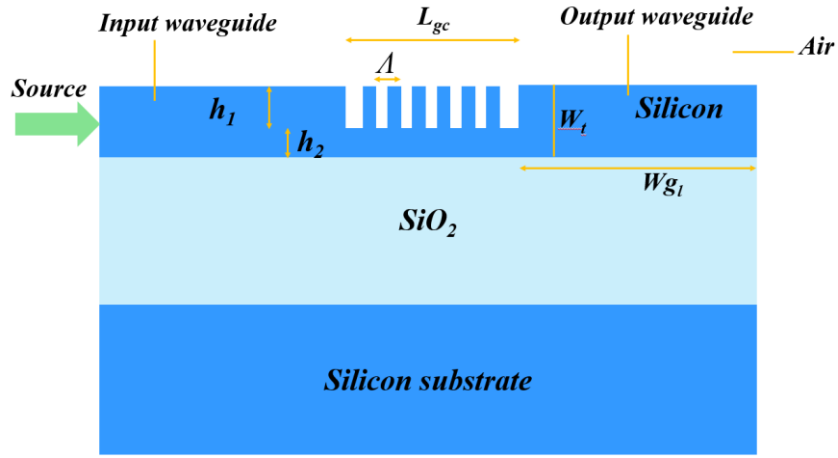
Design of uniform-pitch grating coupler antenna (UGA)

Uniform-pitch grating coupler antenna (UGA) is a GC with uniform pitch over the grating region or grating length (L_{gc}). Standard phase matching condition for GC for first order diffraction is defined by the formula,

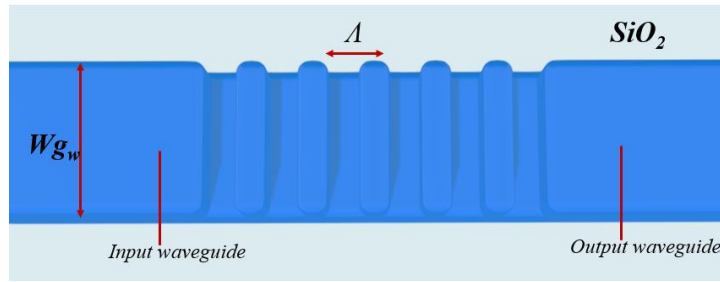
$$n_{eff} = \frac{\lambda}{\Lambda} + \sin \theta \quad (4.1)$$

Here in Eq.(4.1), n_{eff} is the effective refractive index, Λ is the grating period, θ is the coupling angle and λ is the wavelength. In this work UGA realized on SOI platform, with a 2- μm thick silicon substrate used as base substance. On top of the substrate, a buried layer of silicon dioxide (SiO_2) with 2 μm is used as the lower cladding and serves to provide vertical confinement. On top of the lower SiO_2 cladding layer the silicon waveguide layer consisting of input waveguide, grating region and output waveguide is designed to form the optical waveguide (Fig.4.1). Both the output and input waveguide have a length of 10 μm , width of 0.5 μm (W_{gw}) and a thickness of 0.22 μm ($W_t = h_1 + h_2$). Grating region is realised by etching the waveguide core along the W_t with a depth of 0.12 μm (h_1), with grating length of L_{gc} . On top of the waveguide layer, air is used, which will act as upper cladding. Output waveguide is used to collect and carry the power that is not radiated. The designed UGA exhibits a uniform

grating period, Λ .



(a)



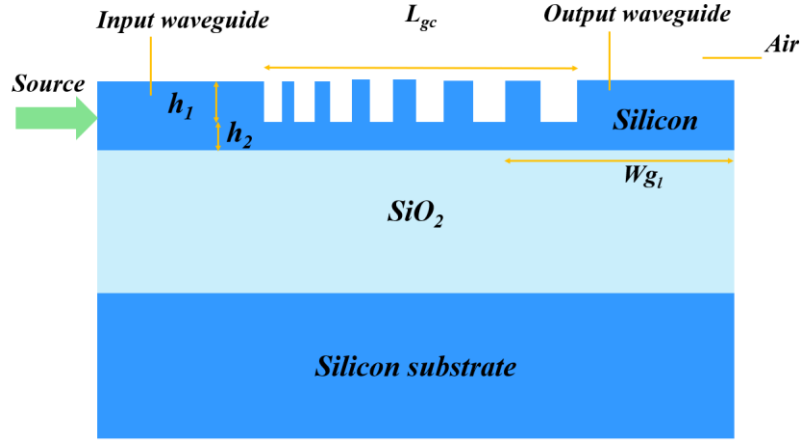
(b)

Fig.4.1 (a) cross-sectional diagram of UGA; (b) Top view of UGA.

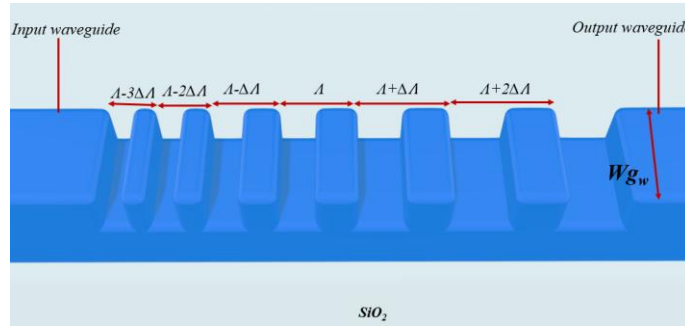
Design of chirped-pitch grating coupler antenna (CGA)

The proposed CGA is designed as a silicon grating coupler on an SOI platform. The antenna dimensions and all the other structural parameters except for the grating pitch, Λ of the designed CGA are exactly the same as those of the UGA. To achieve this broadband operation, the grating pitch is linearly chirped in the propagation direction, varying the local grating period about a central pitch, Λ . These variations in Λ match the wavelengths fulfilling the phase matching condition Eq.(4.1), helps to have achieve broader band width of operation. To compare the two structures the average pitch of the CGA is always set equal to the pitch of the

UGA. The pitch of the grating trend decreases towards the input waveguide and increases towards the output waveguide linearly by $\Delta\Lambda$, as shown in Fig. 4.2.



(a)



(b)

Fig.4.2 (a) cross-sectional diagram of CGA; (b) Top view of UGA.

4.3 Bandwidth Definition and Beam Quality Metrics

Limitations of Conventional Bandwidth Definitions

It is not sufficient to define the bandwidth only in terms of coupling efficiency and radiated power as a function of wavelength for this work. Since our study focuses on fiber to free space coupling rather than fiber to chip coupling, beam profile, angular stability and sidelobe suppression are also key factors. Even if all the above factors are considered while deciding

the bandwidth, the GCA may still suffer from poor Farfield pattern (very much distorted, high sidelobes etc..) though it has meaningful radiation at many wavelengths. Thus, here in this work we tried to proceed with a stricter, more application-oriented definition of bandwidth.

Power Overlap Integral as a Beam Similarity Metric

Power overlap integral is one of the methods that helps to quantify how much similar is the Farfield at a given wavelength to that of the radiation pattern at a reference wavelength [192], [193]. The wavelength which gives the better shape with less sidelobe is manually chosen as reference wavelength. The normalized power overlap integral $\eta(\lambda)$ is defined as

$$\eta(\lambda) = \frac{\iint I_{ref}(\theta_x, \theta_y, \lambda_0) I(\theta_x, \theta_y, \lambda) d\theta_x d\theta_y}{\sqrt{\iint I^2(\theta_x, \theta_y, \lambda_0) d\theta_x d\theta_y \iint I^2(\theta_x, \theta_y, \lambda) d\theta_x d\theta_y}} \quad (4.2)$$

Here in Eq.(4.2), $I_{ref}(\theta_x, \theta_y, \lambda_0)$ represents the far-field intensity distribution at the reference wavelength λ_0 , and $I(\theta_x, \theta_y, \lambda)$ corresponds to the distribution at wavelength λ . Since its normalised $\eta(\lambda)$ has a value between 0 and 1, where higher value indicates the stronger similarity with beam corresponds to reference wavelength. Beam integrity can be systematically studied if the $\eta(\lambda)$ is evaluated strictly over wavelength range of interest. According to our definition, the bandwidth of the CGA includes wavelengths showing $\eta(\lambda) \geq 0.7$.

Beamwidth Evaluation in Orthogonal Directions

Angular confinement of radiated beam can be assessed in terms of beam width, measured separately for the two orthogonal angular dimensions of the two transverse axes of the antenna and is defined as the full width half maximum (FWHM) of the beam. FWHM is defined as the angular width between the points where the intensity in the Farfield beam has dropped to half of its maximum value, and it is wavelength dependent [126], [175]. By evaluating beam width ratio of two orthogonal angular dimension beam distortion can be understood.

Beam width ratio, R can be expressed as,

$$R = \frac{w_x}{w_y} \quad (4.3)$$

Here in Eq.(4.3), w_x and w_y are the width of the beam along X and Y angular direction respectively. In this work we did not explicitly have considered sidelobe suppression, rather a well-shaped and well-focused beam will be manually chosen as a reference beam. As said, the bandwidth of the CGA is defined as the range of wavelengths over which the power overlap integral is given by $\eta(\lambda) \geq 0.7$. For this reason, bandwidth is typically only evaluated in terms of the overlap integral, with the beam-width analysis.

As a primary analysis we started with simulating CGA with chirp increment, $\Delta\Lambda=1.5$ nm, central pitch = $0.55 \mu\text{m}$ and $L_{gc}= 22.5 \mu\text{m}$ (41 pitches) to check if there is any significant bandwidth increment for CGA when compared to UGA. For comparison we used UGA with same parameters, i.e. with same L_{gc} , central pitch and number of pitches. Comparing Fig. 4.3 with 4.4, it is visible that there is an intensity drop while using the CGA when compared to UGA. For UGA and CGA the reference wavelength (λ_{Ref} , wavelength corresponding to the most focused, and best-shaped beam chosen manually) was $1.68889 \mu\text{m}$ and $1.71717 \mu\text{m}$ respectively. It is not surprising to have different λ_{Ref} for the UGA and the CGA. Indeed, an UGA, having the same average period, the same number of periods, the same total length, has a constant period (and thus a constant phase-matching condition) over the entire structure. However, the local variation of the period affects both the radiated field by the antenna aperture, hence the radiated power, and the phase [194], [195], thus changing the antenna aperture distribution. Consequently, this leads to a different interference of the individual radiated elements and to a different far-field radiation pattern [196]. In CGA, the position of maximum spatial coherence and the beam focusing will therefore occur at different wavelengths compared to uniform gratings with the same average structural parameters [187].

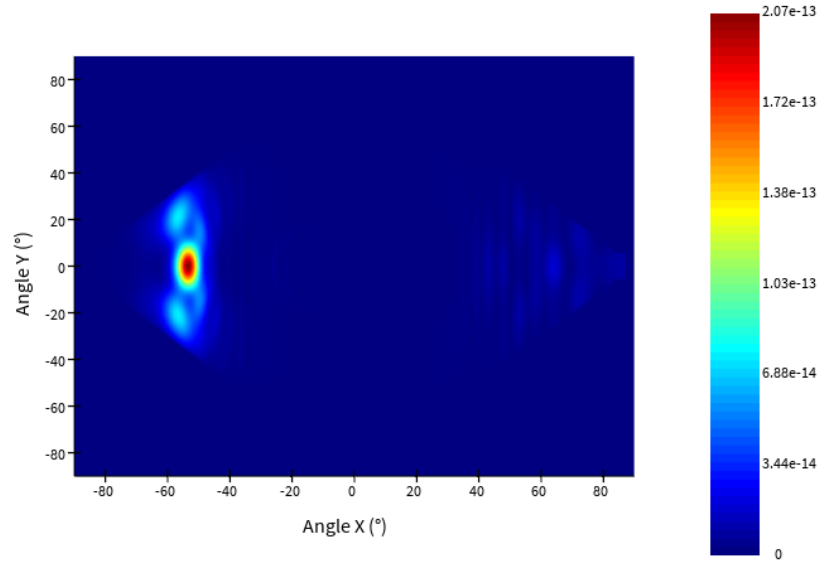


Fig.4.3 Reference beam for CGA with $\Delta\lambda=1.5$ nm.

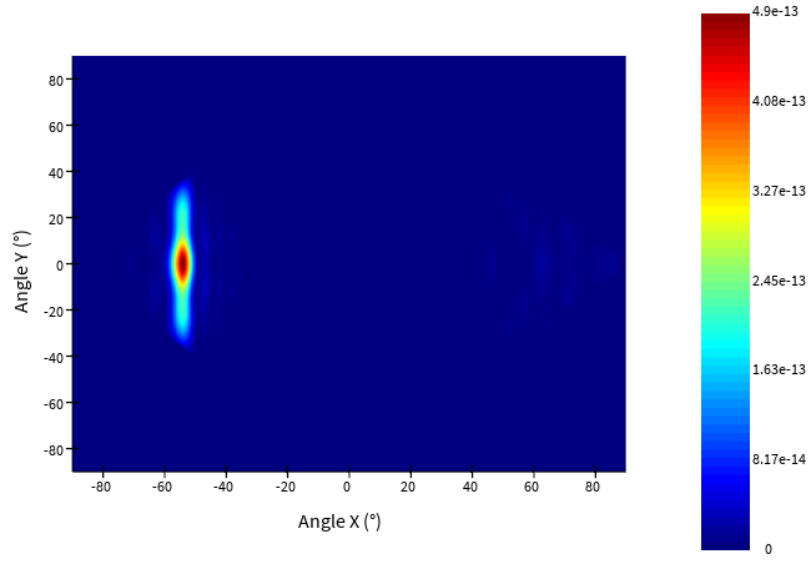


Fig.4.4 Reference beam for UGA with central pitch = $0.55 \mu\text{m}$.

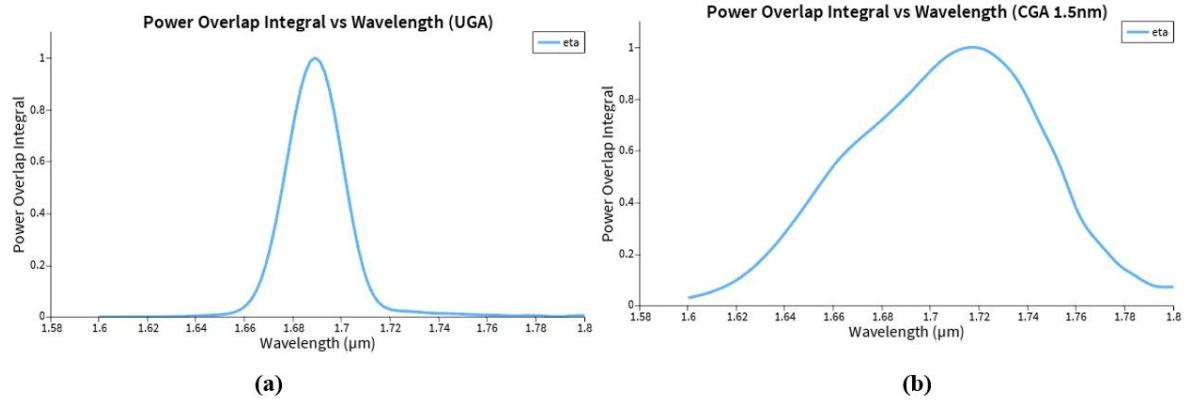
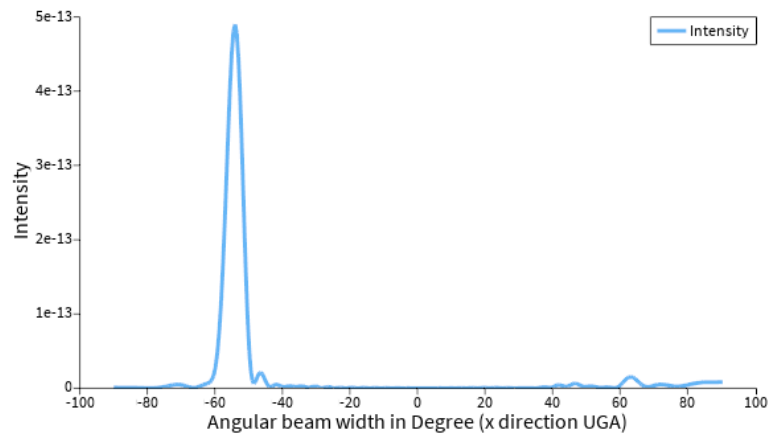
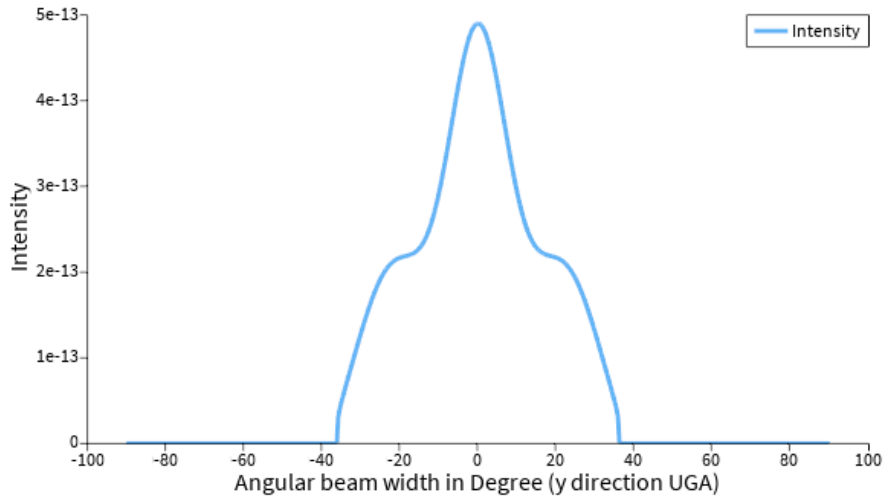


Figure 4.5 Power overlap integral of (a) UGA (b) CGA (1.5nm).

Bandwidth measured ($\eta(\lambda) \geq 0.7$) for CGA was 67.56 nm and for UGA 19.3 μm , hence it is visible that there is significant increase in the bandwidth while using the CGA (Fig.4.5).



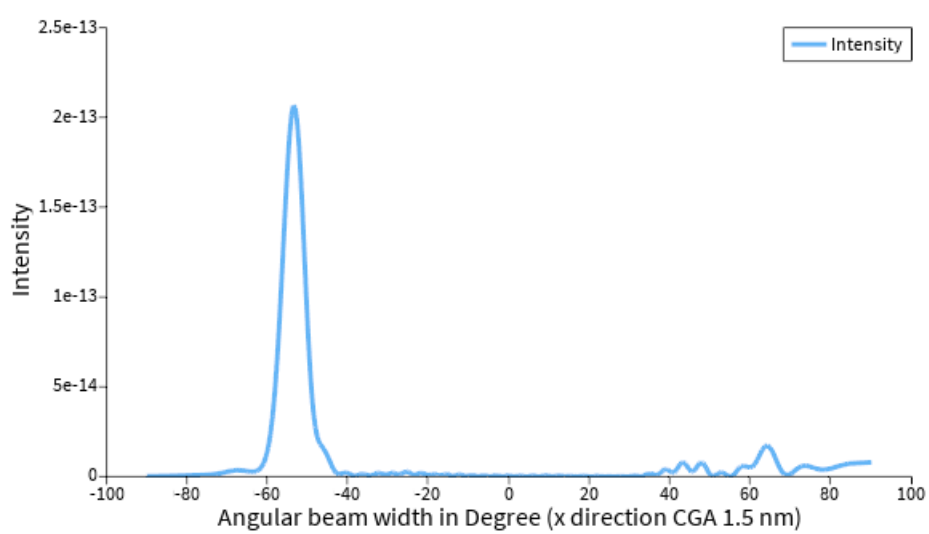
(a)



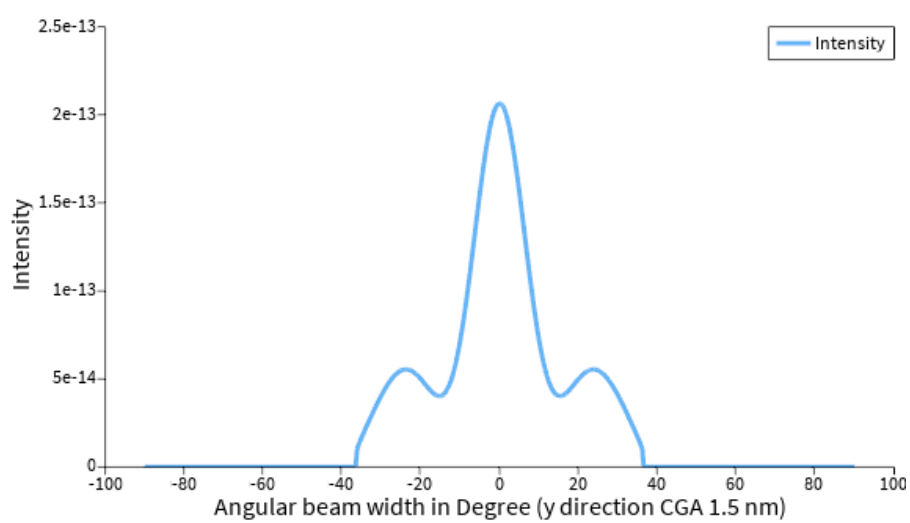
(b)

Fig.4.6 Angular beam width of UGA (a) in x direction (b) in y direction.

The simulated far-field patterns for UGA as shown in Fig. 4.6 (a) and (b) exhibit a FWHM angular beam width of 5.20° and 25.09° in the x and y directions, respectively. The simulated far-field patterns for CGA sketched in Fig. 4.7 (a) and (b) show an FWHM angular beam width of 5.64° and 26.47° in the x and y directions, respectively. The angular spread of the CGA is slightly larger than that of the UGA, implying that although both UGA and CGA have similar overall structures, the elliptical beam of the UGA is a somewhat narrower one.



(a)



(b)

Fig.4.7 Angular beam width of CGA (a) in x direction (b) in y direction.

4.4 Metrics Chirp Increment Optimization

It is confirmed by the previous simulation that the CGA has broader bandwidth than UGA, hence assumed larger chirp increment would phase matching condition over a larger wavelength range and result in a larger bandwidth for the CGA. However, excessive chirping can cause considerable phase incoherence between the contributions to radiation per section of the grating, leading to beam distortion, increased sidelobes and a loss of spatial focus. Therefore, to find a value of chirp increment that can balance the bandwidth and the quality of beam simultaneously. We consider the variation of chirp increment systematically to evaluate this. A set of CGAs are simulated with the same central pitch = $0.55\text{ }\mu\text{m}$ and waveguide geometry differing only in the chirp increment and the L_{gc} and number of pitches. The chirp increments tested were: $\Delta\Lambda=0.375\text{nm}$, 0.75 nm , 1 nm , 1.5 nm and 3 nm with $L_{gc} = 161.55\text{ }\mu\text{m}$, $81\text{ }\mu\text{m}$, $41\text{ }\mu\text{m}$, $21\text{ }\mu\text{m}$ and $11\text{ }\mu\text{m}$ respectively. These lengths are chosen in such way that to keep the chirped pitch variation from $0.52\text{ }\mu\text{m}$ to $0.58\text{ }\mu\text{m}$. The simulated Farfield beam are shown in Fig. 4.8 below and Table 1 represents the simulated results.

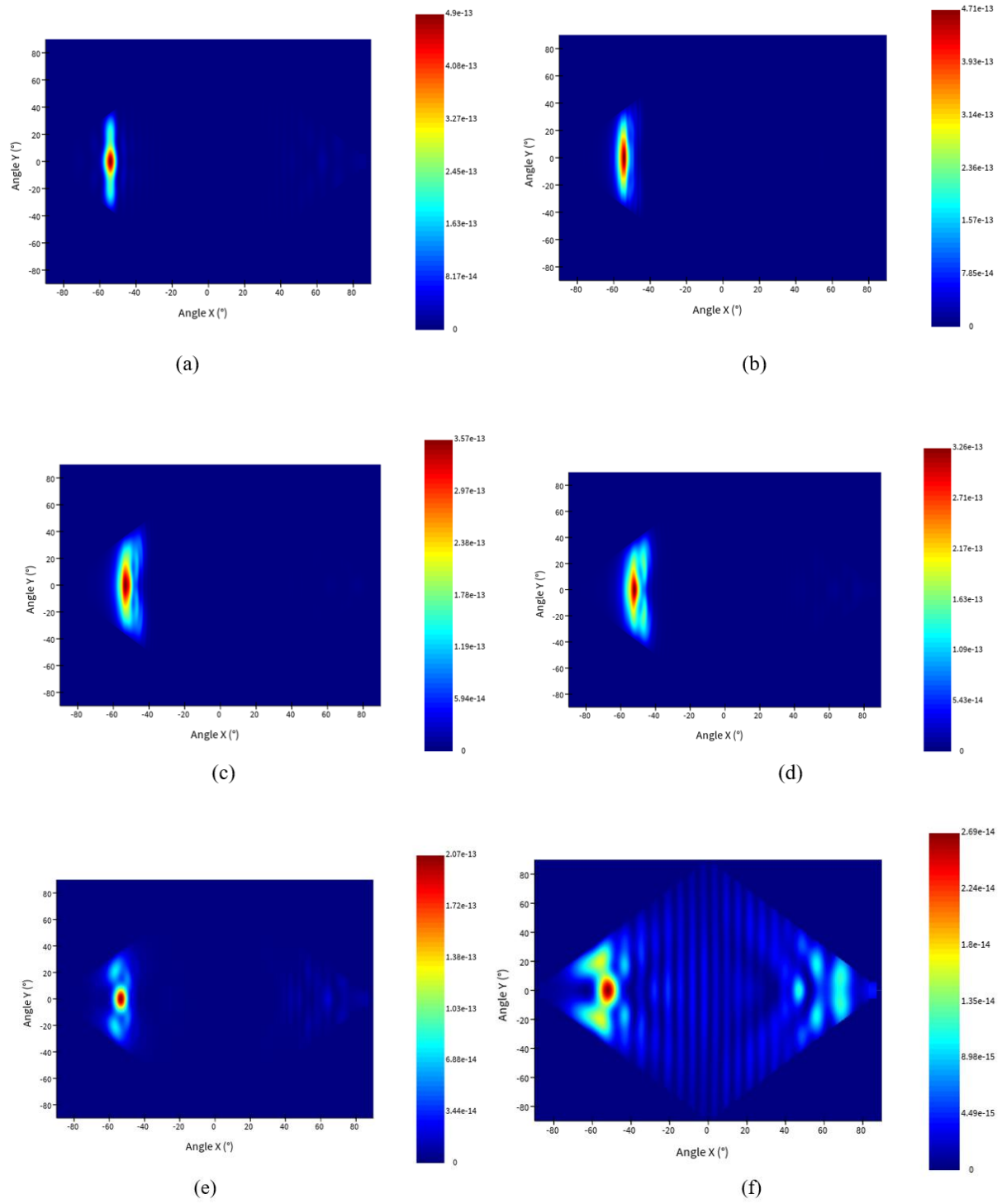


Fig.4.8 Farfield beam for (a) UGA with central pitch $0.5 \mu\text{m}$ CGA with (b) $\Delta\Lambda=0.375 \text{ nm}$, (c) $\Delta\Lambda=0.75 \text{ nm}$, (d) $\Delta\Lambda=1 \text{ nm}$, (e) $\Delta\Lambda=1.5 \text{ nm}$, (f) $\Delta\Lambda=3 \text{ nm}$.

Table 4.1 Effect of chirp variation on beam quality (here W_x and W_y are the width of the beam in x and y direction respectively) and band width.

GCA(μm)	λ_{Ref} (μm)	BW (nm)	w_x ($^\circ$)	w_y ($^\circ$)	Intensity (a.u.)
CGA ($\Delta\Lambda=0.375$ nm)	1.65657	66.15	5	41.3	4.71142×10^{-13}
CGA ($\Delta\Lambda=0.75$ nm)	1.66061	81.54	6.6	44	3.56563×10^{-13}
CGA ($\Delta\Lambda=1$ nm)	1.66465	75.24	6.5	45.56	3.25584×10^{-13}
CGA ($\Delta\Lambda=1.5$ nm)	1.71717	67.56	6.1	16	2.0654×10^{-13}
CGA ($\Delta\Lambda=3$ nm)	1.74141	48.54	9	22	2.6933×10^{-14}
UGA	1.68889	19.3	5.2	25.09	4.9×10^{-13}

Amongst the CGAs explored, the $\Delta\Lambda = 0.75$ nm chirp is found to provide the largest observed spectral bandwidth of 81.54 nm relative to the smaller chirp $\Delta\Lambda = 0.375$ nm case, the larger chirp $\Delta\Lambda = 1$ nm case, the 1.5 nm and 3 nm cases and the UGA reference case. This suggests that slight chirp helps to optimize the distributed phase matching along the grating and maintains reasonable longitudinal coherence along the effective aperture. On the other hand, large chirp leads to larger inhomogeneities of the local phase matching and drives the structure closer to the over-chirped regime, characterized by beam distortion, transverse envelope spreading, and poor radiation output.

The beam-width analysis reveals a dependence on chirp. Around the 1.66 μm wavelength, the beam width in the y direction increases from 41.3° to 44.0° and 45.56° as Δ is varied in steps of 0.375 nm, 0.75 nm, and 1 nm. Meanwhile, w_x stays within a narrow range of 5° to 6.6° . However, in the case of $\Delta\Lambda = 1.5$ nm, w_y reduces substantially to 16° when w_x remains approximately 6.1° . This suggests that chirped structures can support various spectral coherence regimes, and that a larger effective aperture increases the confinement of the beam. For the strongly chirped structure with $\Delta\Lambda = 3$ nm, the beam narrows in x (22°) but strongly diverges in y (9°), whereas the peak intensity is strongly diminished, confirming spatial coherence is lost in the over chirped case. For the UGA, we see intermediate beam widths ($26^\circ \times 6.5^\circ$), which is consistent with the single, spatially homogeneous, phase-matching condition.

This pattern shown at $\Delta\Lambda$, while not the one producing the narrowest single wavelength, has the widest bandwidth (1.63942 μm to 1.72096 μm) and also has a peak brightness that is much higher than that of the case with $\Delta\Lambda = 3$ nm and nearly as high as that of the smallest chirp and uniform one. The idea is that, since the main parameter of interest is the broadening in wavelength, the moderate reduction in peak intensity of the pattern is acceptable in view of the great increase in bandwidth that is obtained along with the stability of the pattern over the larger bandwidth. The wavelength at which the best shape beam can benefit from the chirp increment varies according to the principle on which chirped gratings operate. In the UGA, with no chirp, the phase-matching condition is constant because the period is constant, resulting in a single optimal wavelength (1.68889 μm) for which the radiation is most coherent throughout the aperture. In contrast, CGAs have spatially varying periods. Thus spatially varying phase matching can be achieved. As the chirp increment step increases from 0.375 nm to 0.75 nm, 1 nm and 1.5 nm, the average longitudinal phase redistribution shifts the centre wavelength of the most coherent main lobe to 1.65657 μm , 1.66061 μm , 1.66465 μm . When the chirp is very strong ($\Delta\Lambda = 3$ nm), the optimum shifts to 1.74141 μm , indicating more redistribution of the phase and radiation intensity over the spectrum.

The best overall broad-band beam-steering performance is achieved with a CGA with $\Delta\Lambda = 0.75$ nm as this provides the broadest to sufficient beam confinement and radiation stability whilst avoiding over-chirped operation (which leads to inefficiencies due to the coherence degradation) and under-chirped operation (bandwidth limited). This configuration is thus chosen for the further work.

4.5 Parallel Chirped Grating Antenna Arrays

The chirped grating antenna with a $\Delta\Lambda = 0.75$ nm was chosen for study because of its good spectral and beam-width performance, but it still has meaningful sidelobes and beam distortion. Beam distortion has been studied extensively for grating radiators. Modulating either the duty cycle or the local coupling strength along the length of the grating approximates the Gaussian amplitude distribution of the ideal Gaussian antenna (Apodization). Instead of changing the longitudinal grating profile, parallel sets of identical CGAs can also be formed by closely stacking them together. Number of CGA parallel elements simulated were 3 and 5

and compared with single CGA. A schematic of 5 CGAs placed parallel is shown in Fig. 4.9.

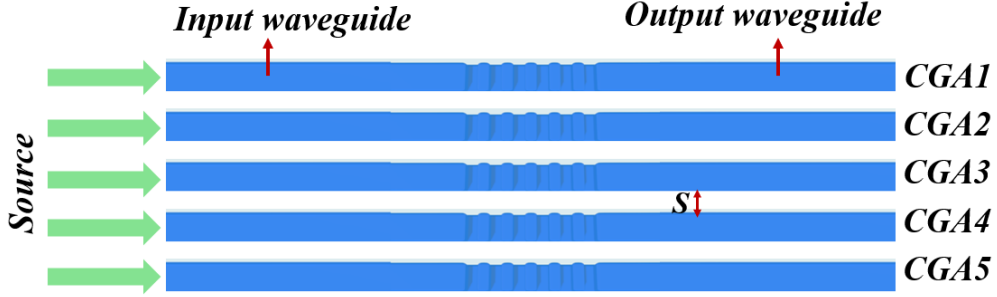


Fig. 4.9 5 parallelly arranged CGAs.

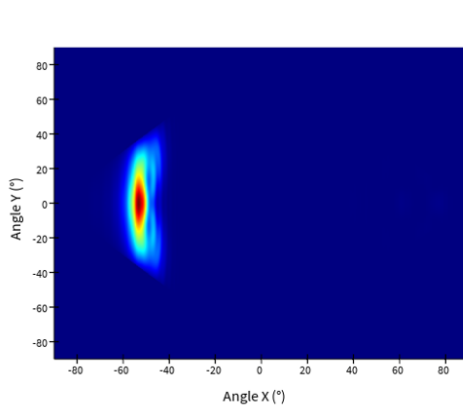
From the simulated far-field patterns (Fig.4.10 (a), (b) and (c) of one, three and five CGA elements respectively, it is observed that the single-CGA far-field pattern has a fairly broad main lobe with some substantial sidelobes because of the finite aperture and the non-uniformly illuminated fields on the grating. The beamwidth in the array axis (the y-direction) is markedly reduced and the sidelobes considerably depressed when three CGAs are arranged in parallel; five CGAs gives an even narrower beam and depressed sidelobes. This is caused by interference between the individual radiators, which reinforce the main lobe, and suppress radiation in other directions. These results are mirrored in Table 2, where it is seen that the beamwidth w_x decreases from 44° for one CGA, to 12.3° for three, and again to 8.56° for five CGAs. Thus we see that more CGAs lead to a greater angular confinement and a better spatial resolution of the beam. However, the beam width does not change much in the y direction (w_y). However, the radiated intensity increases with the number of elements. The radiated power for a single CGA is 3.56×10^{-13} while for a five-element array it is 8.61×10^{-12} . This increase in radiated power is due to coherent power combining and effective transverse radiating aperture increase. This phenomenon can be described rigorously using array theory. For a parallel CGA, the overall far-field pattern is obtained as the product of the element factor (the far-field pattern of a single element) and the array factor.

$$AF(\theta) = \sum_{n=0}^{N-1} e^{jnk_0 d \sin \theta} \quad (4.4)$$

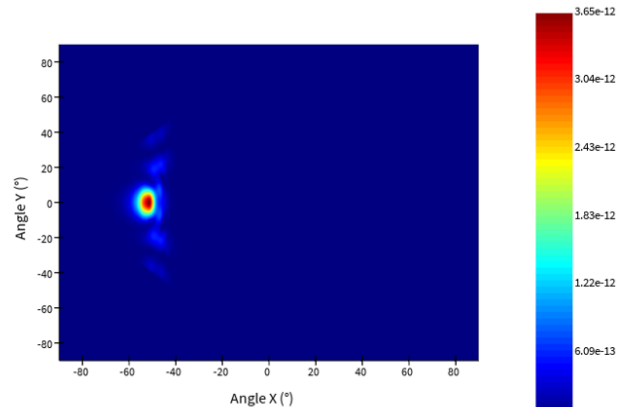
Here in Eq.(4.4), N is the number of elements, and d is the spacing between elements . The main lobe of the array factor radiation pattern narrows as the number of parallel CGAs increases, redistributing the power more heavily to constructive interference in the steering direction and destructive interference in all other directions. Consequently, a larger number of elements results in a larger transverse aperture, a larger directivity, and in lower relative sidelobe levels.

Table 4.2 Effect of number of parallelly placed CGAs on beam quality.

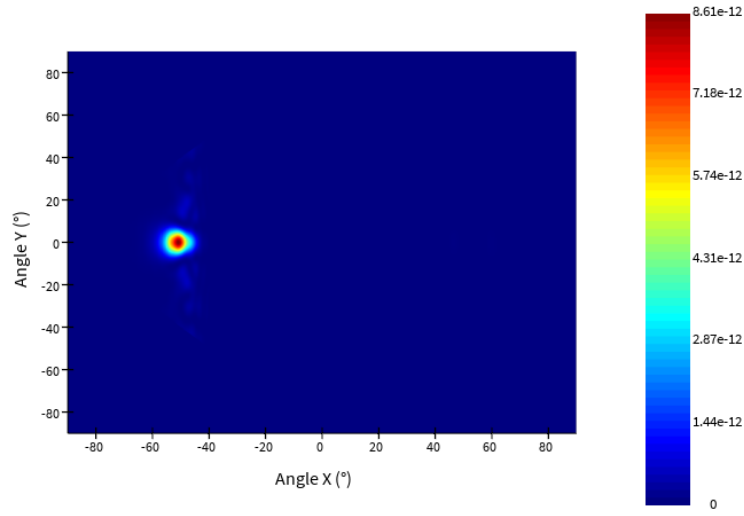
Number of parallelly placed CGAs	w _x (°)	w _y (°)	Intensity (a.u)
1	6.6	44	3.56563×10^{-13}
3	6.1	12.3	3.64×10^{-12}
5	7	8.56	9.59×10^{-12}



(a)



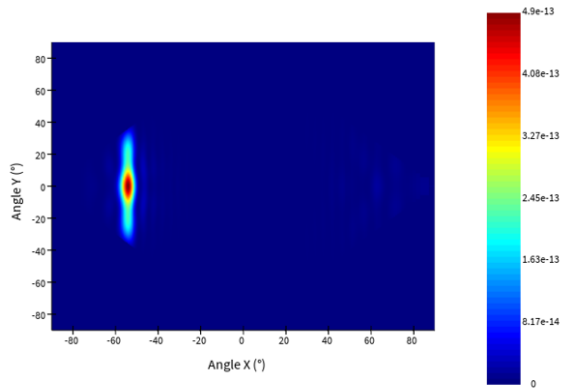
(b)



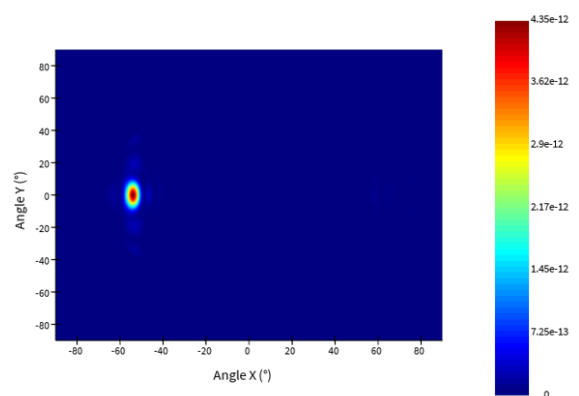
(c)

Fig.4.10 Farfield beam of CGAs in parallel (a) one element (b) three elements (c) five elements.

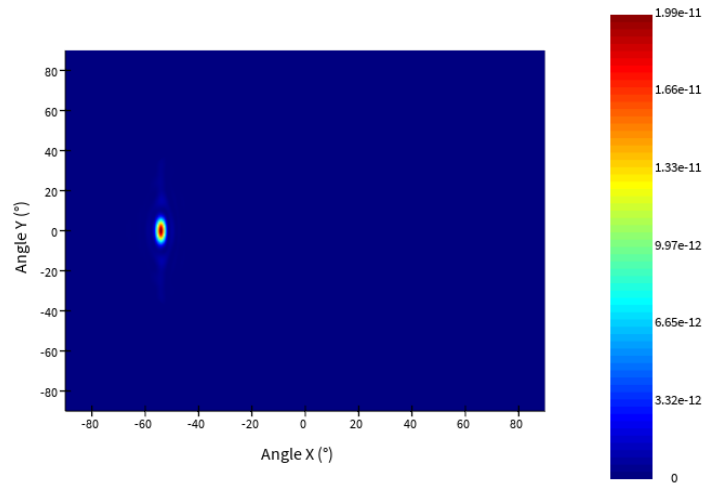
Ensuring that compact integration avoided unwanted crosstalk, coupling between the waveguides was measured across a parallel length of $44.55 \mu\text{m}$ across the entire operating band ($1.64\text{-}1.72 \mu\text{m}$). For a separation of $S = 1.5 \mu\text{m}$, no more than -20.6 dB (1%) of the power was coupled into the adjacent waveguide across the whole band confirming that there was negligible evanescent coupling. A $1.5 \mu\text{m}$ separation can therefore be practically maintained without considerably compromising crosstalk or degrading the radiation performance.



(a)



(b)



(c)

Fig.4.11 Farfield beam of UGAs in parallel (a) one element (b) three elements (c) five elements.

Table 4.3 Effect of number of parallelly placed UGAs on beam quality.

Number of parallelly placed UGAs	w_x (°)	w_y (°)	Intensity (a.u)
1	6.5	26	4.9×10^{-13}
3	12.235	12.23	4.35×10^{-12}
5	4	9	1.9×10^{-11}

From the simulated far-field patterns (Fig. 4.11 (a), (b) and (c) of one, three and five UGA elements respectively, similar effect on intensity and beam quality is observed as seen in the case of CGAs, the results are given in Table 4.3. Now the beam quality of CGAs is comparable with UGAs with an advantage of broad bandwidth (for CGA). Thus, sidelobe suppression and concentration of the beam can be achieved simultaneously with ultra-close spacing through parallel integration of multiple CGAs. The improved radiation efficiency can be understood from the theory of phased arrays. Weak coupling between adjacent waveguides enables dense integrated beam steering from parallel CGA arrays.

4.6 One-dimensional beam steering mechanism

True beam steering requires that the emitted beam is steerable independently along two different angular dimensions, which requires that the emitters embedded in the PIC be agile in the phase difference between the emitters and in the emission angle of each individual radiator.

In this work for steering in y direction, phase differences are introduced between the input sources (Fig.4.9) of parallel CGA separately.

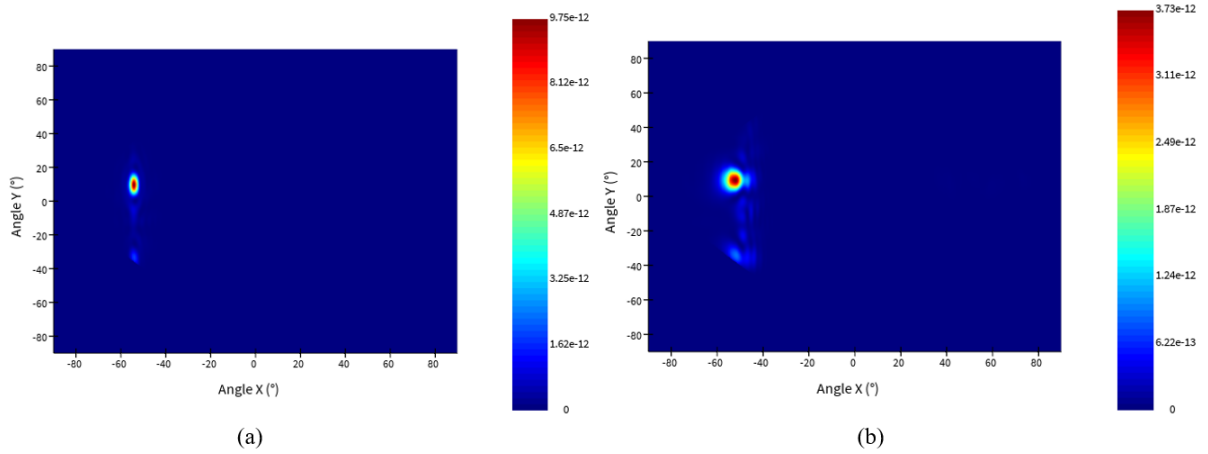


Fig.4.12 Farfield beam of (a) 5 parallel UGAs with 80° phase shift (b) 5 parallel CGAs with 80° phase shift.

In the case of the five-element UGA and CGA arrays, the application of a 80° , (beyond that the beam become distorted with side lobes) phase shift between adjacent antennas caused a phase shift of the main beam being steered from its zero-phase direction. The degree of steering caused by this phase shift is approximately 10° (centre to centre angular distance) towards the line of the array (Fig.4.12) for both UGA and CGA. The UGA has higher peak intensity and a narrower beam width in the horizontal direction, but the CGA has a wider radiation pattern in the horizontal direction. The intensity peak may decrease because of phase steering. In spite of this, the broad bandwidth of the CGA makes it more suitable for integrated 1D beam steering.

To steer the beam in the second dimension (x direction), using a matrix of CGAs having an average pitch varying along x direction is proposed as shown in Fig. 4.13. Each blue rectangle is composed of 5 parallel CGAs (optimized) with different pitches arranged along x direction. The three sets consisted of average wavelengths of 530 nm, 540 nm, and 550 nm, illuminated separately. After arranging, the resulting beam positions were then observed at a wavelength of 1.66061 μm for each pitch configuration.

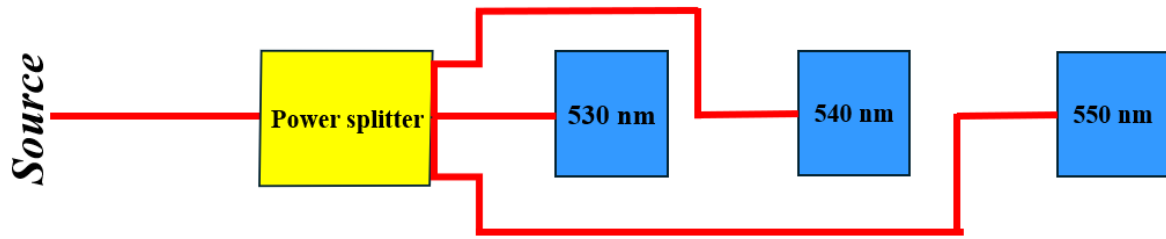


Fig.4.13 Layout and beam steering of the CGA matrix. The configuration uses three sets of 5 parallel chirped grating antennas (blue rectangles) with average pitches of 530 nm, 540 nm, and 550 nm. Independent illumination is confirmed a lateral beam shift corresponding to each unique pitch.

The beam steering in the x-direction is calculated using the far field responses of five CGAs in parallel with an average pitch of 530 nm, 540 nm, and 550 nm at the wavelength of 1.66061 μm as shown in Fig. 4.14. The matrix is then compared with an equivalent configuration of UGAs at the wavelength of 1.68889 μm to highlight the improvement in beam steering bandwidth achieved by using the CGAs. To replace the three CGAs in Fig. 4.13, we consider five parallel UGAs with pitches of 530 nm, 540 nm, and 550 nm, and observe their far-field distributions (Fig. 4.15).

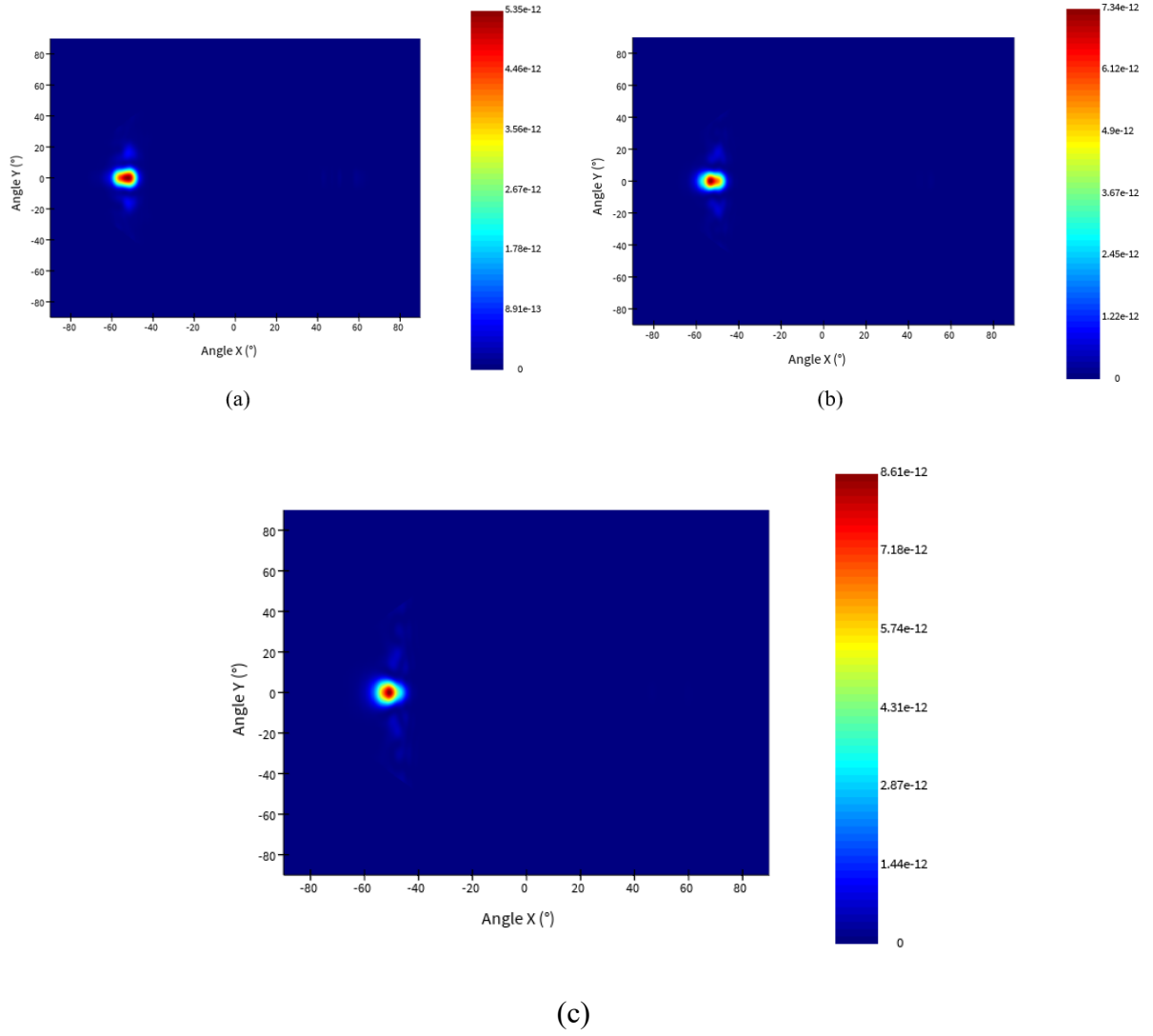


Fig.4.14 Farfield beam of CGA matrix with avg pitches (a) 530 nm, (b) 540 nm, and (c) 550 nm.

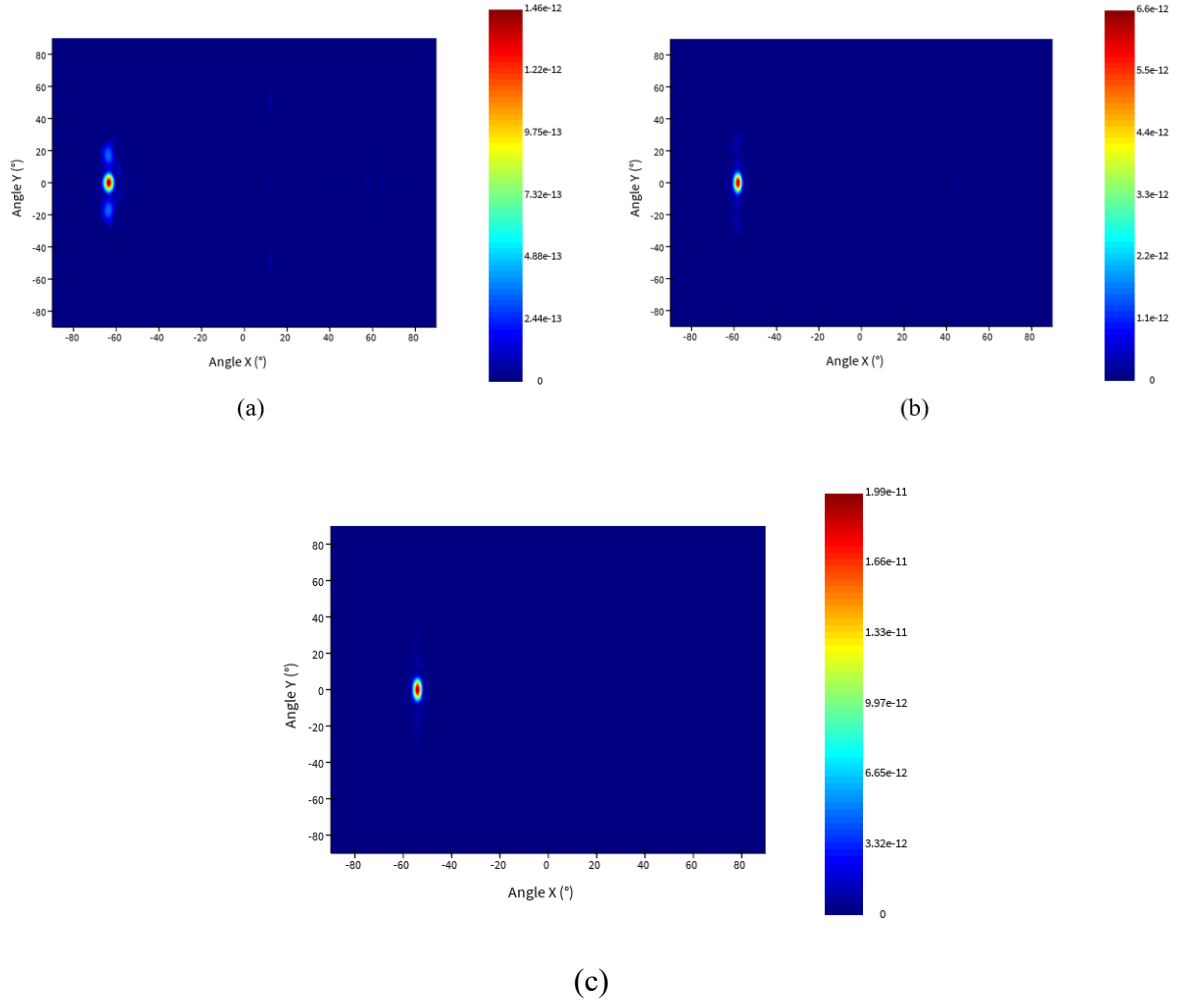


Fig.4.15 Farfield beam of UGA matrix with pitches (a) 530 nm, (b) 540 nm, and (c) 550 nm.

The radiation pattern of the CGA elements at average pitches of 530 nm, 540 nm, and 550 nm is shown in Fig. 4.14. As shown, although the structure is not fully optimised, the overall beam pattern is fairly constant throughout the range of selected pitches without side lobes. Meaning the CGA is stable with respect to radiation across changes in average pitch attempting to optimise the structure are applied. However, Fig. 4.15(a) corresponding to the UGA configuration has a well-defined main lobe, but has meaningful sidelobes in the far-field pattern. This suggests that the UGA array is faster at pitch, but not as good at beam steering. Taken all together, this hints that the CGA structures would be a better choice to steer the beam, since the beam profile doesn't change as much with structural variations, unlike the UGA array. The degree of steering with the matrix of UGA (from pitch 530 nm to 550 nm) is around 10 degrees, but surprisingly the degree of steering for CGA is around 3 degrees, this

should will be studied further. By combining the mechanisms used for beam steering in x and y direction i.e. structural tuning and phase 2D beam steering can be obtained.

4.7 Rise time (t_r)

The rise time (t_r) of a LiDAR system determines its time resolution, i.e. the system's ability to separate closely spaced target and response pulses and to detect rapid optical transients.

The t_r is commonly defined as the time interval between 10% and 90% of the peak height of the response of a detected signal [197]. In case of photonic detectors, the rise time is frequently used to quantify the speed of their response and is inversely related to the system bandwidth [198]. For a Gaussian system with a defined bandwidth, an equivalent rise time t_r can be approximated as,

$$t_r = \frac{0.35}{\text{Bandwidth}} \quad (4.5)$$

revealing a relationship so that higher bandwidth results in faster temporal resolution. Thus, the bandwidth of the system will define the limit of achievable temporal resolution [199][200].

Bandwidth in Eq.(4.5) can be written as,

$$\text{Bandwidth} = \frac{c}{\lambda^2} \Delta\lambda \quad (4.6)$$

Here λ is the central wavelength, and $\Delta\lambda$ is the bandwidth in terms of wavelength. Since bandwidth of CGA is from 1.63942 μm to 1.72096 μm , and for UGA is from 1.67912 μm to 1.69842 μm , their central wavelength of CGA and UGA is 1.68019 μm and for 1.68877 μm , respectively. The CGA, with a bandwidth of 81.54 nm, exhibits a significantly reduced t_r of approximately 40 fs compared to 172 fs for the UGA, demonstrating its superior temporal response and suitability for LiDAR application.

4.8 Conclusion

In this chapter we have investigated the use of grating based optical antennas for radiation domain beam steering, focusing on chirped grating coupler antennas that can be fabricated using a silicon-on-insulator (SOI) substrate. We started with the design and characterization of a UGA that is used as a reference to study the radiated far-field properties of the chirped antennas. However, due to the small bandwidth of only 19.3 nm, an alternative strategy is pursued involving CGA, where the pitch of the grating is varied along the length of the radiating aperture, allowing radiation to occur not for a single wavelength, but for a wide spectral bandwidth.

The dependence of different chirp increments on the antenna's spectral bandwidth, the beam quality and the radiation stability was systematically investigated. It was possible to achieve an important improvement of the antenna's spectral bandwidth while preserving the spatial coherence if only moderate chirp increments were used. The most homogeneous performance was achieved for the CGA with a pitch increment of $\Delta\Lambda = 0.75$ nm and a total length of 44.55 μm . The achievable operational bandwidth was 81.54 nm, which is four times greater than that of the uniform grating antenna. Smaller chirp increments did not improve bandwidth considerably, while larger increments increased a phase mismatch along the whole grating, resulting beam spreading and loss of beam quality. Thus, the chirped grating antenna with 0.75 nm chirp was chosen as the best candidate for further study of beam steering.

To further improve the radiation performance and reduce the side lobes, several chirped grating antennas were placed one beside the other in parallel, effectively increasing the radiating aperture. Configurations of three and five parallel CGAs were implemented and compared against the performance of a single antenna. The results of these calculations show that both the beam confinement and the side-lobe level improve greatly as one increases the number of antennas. The beam-width in the y-direction shrank from about 44 degrees in the case of a single CGA to 12.3 degrees in the three-element case and about 8.56 degrees in the five-element case. The radiated intensity, on the other hand, is found to be more than an order of magnitude larger, due to the coherent power combining of the individual emitters. At the same time, the beam width in the x-direction remains constant. Thus, the narrowing occurs parallel to the array axis.

Later the optimized CGA configuration was measured for its 1D beam steering capabilities. The y-direction beam-steering is realized by providing the phase shifts to the source signals of the parallel CGAs. Due to the considerably higher bandwidth of the CGA antennas, the same calibration procedure can be performed using only the phase difference in Eq. from (4.1), yielding the effective phase scaling factor necessary to provide the required phase to direct the beam at the desired angle. In the far field, the maximum phase difference between the two antenna elements was limited to about 80° . Larger differences in phase gave rise to many secondary maxima and an undesirable antenna pattern. For the two antenna designs (uniform and chirped grating) the steering range is approximately 10 degrees.

Once we achieved the steering in y direction, we introduced a matrix of chirped grating antenna (or uniform grating antenna) in x direction. Even though we are able to steer the beam in x direction with UGA around 10 degree, the beam steered with CGA in x direction was around 3 degree, further studies will be conducted on this.

Finally, we calculated the rise time for both CGA and UGA and concluded CGA is more suitable for applications like LiDAR since have fast rise time.

In summary, we have shown that chirped grating antenna engineering provides a reliable solution towards achieving broadband radiation and better time response within the integrated photonic platform. The optimized 0.75 nm chirp increment and the phase control mechanism of parallel CGA arrays enable meaningful improvement in spectral bandwidth, beam confinement and side lobe level in comparison with a standard uniform grating antenna. These results show chirped grating antennas as small and efficient radiators for integrated photonic beam steering architectures with broadband functionality. Comparative analysis of integrated photonic beam steering architectures including uniform grating antennas (UGA), chirped grating antennas (CGA), phase-domain optical phased arrays and delay-domain (TTD) systems in terms of a number of relevant performance metrics including bandwidth, beam stability, wavelength and time response and system complexity is shown in Table 4.4.

Table 4.4 Comparison of CGA-based beam steering with other photonic beam steering approaches.

Parameter	UGA	CGA	Phase domain OPA	TTD
Primary role	Radiating antenna	Radiating antenna	Phase-control architecture	Time-delay control architecture
Operational bandwidth	Narrow	Broad	Narrow– moderate	Broad
Steering principle	Mainly wavelength dependent	Structural + phase-assisted	Spatial phase gradient	True time-delay gradient
Beam-squint sensitivity	High	Lower than UGA	High	Low
Control complexity	Low	Low–moderate	High	High
Footprint / implementation cost	Compact	Compact– moderate	Moderate–high	High

Conclusions

This thesis work involved the study and development of integrated photonic beam steering architectures to overcome the limitations of mechanical and electronic beam steering solutions. The wide-spread adoption of compact, broadband and high-speed beam steering solutions for communication and sensing applications is anticipated to be enabled by integrated photonic architectures, providing features such as wide-bandwidth operation, low-loss signal distribution and resistance to electromagnetic interference. In this context, this thesis investigated how to implement delay-domain, phase-domain and radiation-domain beam steering, in PIC platforms.

The first part of the work proposes delay-domain beam steering through integrated photonic true time delay (TTD) beamforming architectures. TTD beamforming enables frequency-independent steering by applying temporal delays between antenna elements to steer the beam. This alleviates the beam squint, the dispersion of the beam direction with respect to the wavefront direction, observed with all phase shifters based on conventional phase shifters in broadband phase-based beamforming networks. Analysis of integrated photonic delay systems has indicated that they provide broadband MWP beamforming in a compact form factor with stable beam steering.

The latter half of this thesis focused on phase-domain beam steering. Optical phased arrays (OPAs) are a large array of optical emitters on a photonic chip that are able to steer a beam by modulating the phase difference between the emitters. The influence of the array configuration and phase control on the far field output was investigated. However, it demonstrated that the incorporated OPAs could create a coherent beam through the constructive interference of the emitters. By optimizing the emitters' design and the array configuration, the beam divergence and side-lobe effect can be minimized.

The final chapter covers radiation-domain beam steering of engineered grating-based optical antennas, specifically chirped grating coupler antennas (CGAs). A systematic alteration of the chirp increment revealed that a 0.75 nm increment provides the best trade-off in bandwidth and beam profile quality. The bandwidth, defined by this increment, of the CGA was 81.54 nm, which is larger than the bandwidth of the uniform grating antennas which is 19.3 nm. The

beam confinement and side lobe level were further improved by arranging the CGA antennas in parallel, which increases the effective radiating aperture. Up to five parallel configurations were measured, forming a highly-narrowed beam with radiated power gain and virtually no inter-waveguide coupling, at 1.5 μm gap spacing, between the waveguides. An optimized chirped antenna architecture also allowed for broadband two-dimensional beam steering, with wavelength dependent radiation accommodating steering in one direction and phase control of the emitters providing steering in the orthogonal direction.

The experimental results in the present thesis conclusively show that true time delay beamforming, optical phased arrays and radiation engineered grating antennas can provide integrated photonic devices with high-performance beam steering with respect to spectral bandwidth, beam quality and compactness. The proposed design concept of a chirped grating antenna is thus promising for future integrated photonic-based beam steering technologies. This study allows the development of scalable photonic beamforming technologies for LiDAR, optical wireless communication, remote sensing, and microwave photonic signal processing applications.

Future work may include the experimental realization of the proposed architectures, the implementation of active phase tuning elements for dynamic and efficient beam steering, as well as further development of radiation engineering approaches for improved beam quality and steering efficiency in fully integrated photonic BS systems.

List of Publications

Journal

[j1] R. Kutteeri, M. De Carlo, F. De Leonardis, R. A. Soref, and V. M. N. Passaro, "Phase-Change-Material-Based True Time-Delay System," *Sensors*, vol. 24, no. 23, Art. no. 7613, Dec. 2024, doi: 10.3390/s24237613.

Conference Proceedings

[c1] R. Kutteeri, M. De Carlo, F. De Leonardis, and V. M. N. Passaro, "Two-dimensional beam steering by cascaded domain engineering in lithium niobate," in *Proc. 25th Anniv. Int. Conf. Transparent Opt. Netw. (ICTON)*, Barcelona, Spain, 2025, pp. 1–6, doi: 10.1109/ICTON67126.2025.11125231.

[c2] R. Kutteeri, M. De Carlo, F. De Leonardis and V. M. N. Passaro, "Optimising brightness and power enhancement trade-off in Cerium doped YAG 3D luminescent concentrator," *2025 25th Anniversary International Conference on Transparent Optical Networks (ICTON)*, Barcelona, Spain, 2025, pp. 1-4, doi: 10.1109/ICTON67126.2025.11125293.

[c3] R. Kutteeri, M. De Carlo, F. De Leonardis, R. A. Soref, and V. M. N. Passaro, "True time delay system using phase change materials," in *Lecture Notes in Electrical Engineering*, 2025, pp. 341–347, doi: 10.1007/978-3-031-71518-1_41.

[c4] R. Kutteeri, M. De Carlo, F. De Leonardis, R. A. Soref, and V. M. N. Passaro, "Integrated Phased Array Antenna Using Phase Change Materials," in *Proc. AES 2024, International Conference on Antennas and Electromagnetic Systems*, Rome, Italy, Jun. 2024, pp. 1–4 (p. 1).

Appendices

Appendix A: Phase-Change Materials for Non-Volatile Programmable Optical Delays

A.1 Physical Mechanism of Optical Phase-Change Materials

Phase-change materials (PCMs) can be switched between an amorphous and crystalline state, for which their optical and electrical properties vary considerably. The changes between phases are achieved by the application of heat at the nanoscale by electrical or optical pulses which cause the atomic bonds to change their configuration. Because the PCM preserves its state after the stimulus is removed, these materials are non-volatile and are a promising candidate for programmable photonic devices.

The lattice is said to undergo a phase transition involving atomic rearrangement at its transition temperature, wherein the amorphous phase possesses an unordered atomic structure, becoming more ordered in the crystalline phase. Furthermore, this modification can affect the electronic band structure, the polarizability, and the complex refractive index of the PCM. Therefore, the optical phase and propagation characteristics of the guided light can be dynamically modulated when a PCM is integrated with a photonic waveguide.

The two transitions have different thermal processes:

- Crystallization: Heating the material above the crystallization temperature, T_c allows the atoms to arrange themselves into a lattice.
- Amorphization: Heating above the melting temperature, T_m followed by rapid cooling, results in an amorphous structure.

Because the states are non-volatile, PCMs enable non-volatile reconfigurable photonic components such as switches, phase shifters, filters, and optical delay lines.

A.2 Antimony Trisulfide (Sb_2S_3) for Photonic Phase-Change Devices

Antimony trisulfide (Sb_2S_3) is a low-loss, high-contrast refractive index-contrast PCM with potential for integrated photonics. The refractive index of Sb_2S_3 changes considerably in the near-infrared range around 1550 nm, with a refractive index of amorphous state 2.712 and crystalline state 3.308 resulting in a refractive index contrast of $\Delta n \approx 0.6$, while maintaining lower optical absorption than conventional phase change materials (PCMs) such as GST.

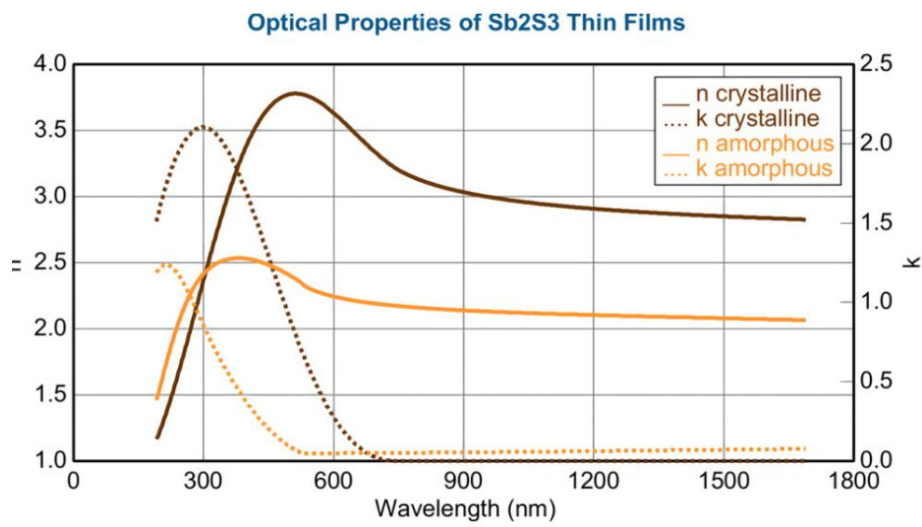


Fig.A.2.1 Refractive index and extinction coefficient of amorphous and thermally crystallized Sb_2S_3 thin films determined with spectroscopic ellipsometry. The crystalline film shows a higher refractive index n , a higher extinction coefficient k , and a red-shifted absorption edge compared to the amorphous film. The absorption onset shifts from 528 nm in the amorphous film to 743 nm in the crystalline film. [201]

Sb_2S_3 is optically transparent over a range of approximately 0.35 to 4.5 μm , making it useful for photonic applications in the visible through near infrared range. Crystallization of Sb_2S_3 from amorphous Sb_2S_3 occurs at approximately 573 K, while amorphization requires heating above the melting point (approximately 823 K) followed by rapid quenching [139]-[143].

A.3 Optical Delay Programming Using Sb₂S₃

When Sb₂S₃ is integrated with a photonic waveguide, this transition alters the refractive index of the optical mode guided by the structure. The optical phase and propagation delay are modified by:

$$\tau = \frac{n_{eff}L}{c} \quad (A.1)$$

Where, n_{eff} is the effective refractive index of the waveguide mode, ‘L’, length of the PCM-integrated waveguide section and ‘c’ is the speed of light in a vacuum.

Programmable optical delays can be realized via selective phase modulation in different segments of the waveguide. As the phase state can be retained without the need for continuous electrical bias Sb₂S₃ has potential for non-volatile programmable delay lines, microwave photonic beamforming networks and integrated optical phased arrays. The thermal transition parameters of Sb₂S₃ are typically reported as, $T_c \approx 573K$ and $T_m \approx 823K$.

Appendix B

Below presents additional work done during this PhD on the trade-offs in power and brightness enhancement in Cerium-doped YAG three-dimensional luminescent concentrators. The work also derives a new metric, the Brightness-Power Trade-off Index (BPTI), which indicates the optimal aperturing ratio to achieve maximum brightness without exceeding a desired power output.

This study investigates the intrinsic trade-off between brightness enhancement and power enhancement in Cerium doped YAG 3D luminescent concentrator. This work explicitly quantifies the inverse proportional nature of these two parameters and proposes a new parameter called Brightness Power Trade-off Index to optimize the relationship. The results highlight the importance of selecting an optimal aperturing ratio, which helps in designing efficient luminescent concentrators for practical applications.

Introduction

Designing a light source which can provide high power and higher brightness is still a challenge. The available coherent light sources lack high power while providing high brightness, in the case of incoherent light sources, it occurs the opposite. Several studies have been carried out and still going on either in focusing on brightness enhancement of existing incoherent sources [202], [203] or power enhancement of coherent sources [204], [205]. Brightness enhancement refers to the increase in the radiance (brightness) achieved by concentrating the emitted photons into a smaller emission area.

Light recycling is one of the suggested approach for higher brightness light sources based on the existing powerful incoherent sources [202], [206]. Light recycling is a process of sending back a portion of emitted light to the emitter. The emitter should be partially reflective or transmissive so this portion of light will combine with direct emission and thereby help to enhance the brightness. This concept of light recycling has been investigated for thermal emission in discharge lamps [207], [208], infrared part of spectrum in light bulbs [209] and light emitting diodes (LEDs) [210]. Placing the emitter inside a cavity having high reflectivity can enhance the brightness up to some extent [211]. However, brightness in lamps is limited

by absorption caused by the emitter. Then, to achieve a better brightness enhancement, low absorption emitters and low loss emitting media should be used. Ce:YAG luminescent concentrator (LC) is an example of such emitting media, producing incoherent emission via luminescence (fluorescence).

LC is a slab that confines and guides the light emitted by luminophores/phosphors (embedded on LC) using the total internal reflection (TIR) mechanism. This guided light is collected at four small edges of the slab using photovoltaic cells. A light source is required to pump the luminophore in LC, which can be sun (Luminescent Solar Concentrator) or other light sources like LEDs. Depending on how the light is confined in LC, they can be classified in 1D [208], 2D [209] and 3D LCs [202].

A previous theoretical and experimental study was published [202] for the brightness enhancement using 3D LC for Ce:YAG. It was focused on designing and developing a light source combining power, brightness and incoherence via light recycling. But because of light recycling, loss of emitted power is reported. In this study we focus on the inherent trade off between brightness enhancement and the output power of Ce:YAG 3D LC. This paper is structured as follows: background discussion explains the theory behind 3D LC and brightness enhancement using it. In results section we explore the inherent trade-off between brightness enhancement and power enhancement of 3D LC and, lastly, the discussion and conclusions are summarized, respectively.

Background Discussion

Fig.B.1 illustrates the structure of 2D LC. 3D LC is designed by adding highly reflecting mirror with area S in the output face of 2D LC and by further leaving small aperture in the mirror. Aperture has an area s for allowing recycled light to pass through it, as in Fig.B.2a, being $r=S/s$ is the aperturing ratio. As r decreases, the brightness enhancement increases. The D shaped closing mirror is chosen as it minimizes the obstruction of light emitted at wide angles, as sketched in Fig.B. 2b.

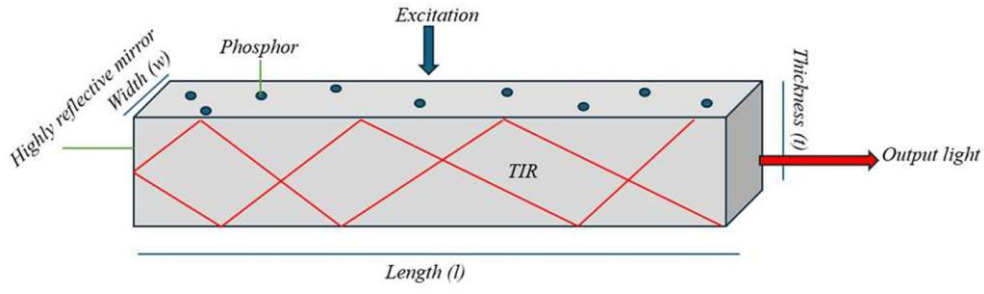


Fig.B.1. Illustration of luminescent concentration of 2D LC.

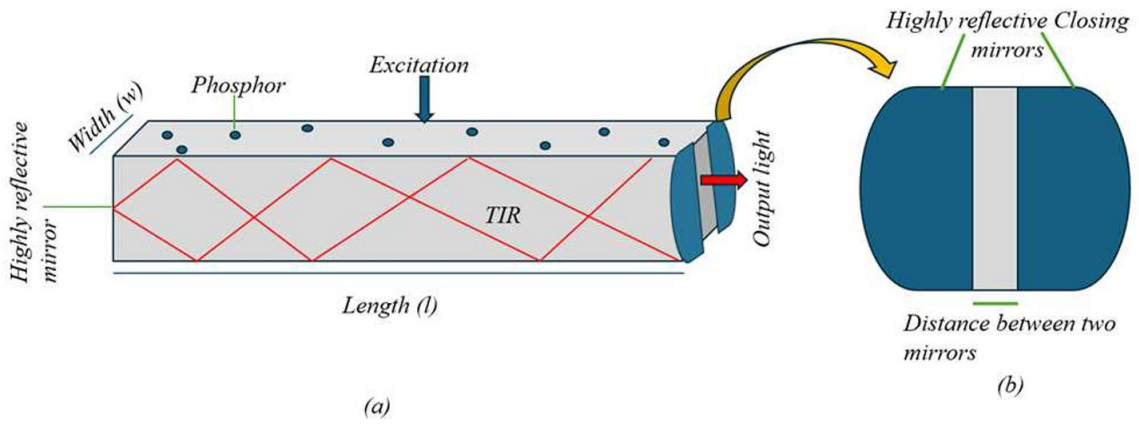


Fig.B.2. (a) Illustration of luminescent concentration in 3D LC (b) Enlarged view of output face with D-shaped closing mirrors in 3D LC.

Considering 2D LC the total power emitted by the output face is P_{2D} , which can be calculated as:

$$P_{2D} = (P_1 + P_2) \frac{T_{Fresnel}}{1 - e^{-2\alpha d} R (1 - T_{Fresnel})} \quad (B.1)$$

In Eq.(B.1), P_1 is the power of rays emitted directly towards output face without undergoing any reflection, which can be expressed as in Eq. (B.2), while $T_{Fresnel}$ is calculated as in Eq. (A.B.3), where n is the refractive index of LC.

$$P_1 = \frac{n_t S \phi_e}{2\alpha \ln(\cos \theta_{max})} (1 - (\cos \theta_{max})) (e^{-\alpha d} - 1) \quad (B.2)$$

$$T_{Fresnel} = 1 - \left(\frac{n - 1}{n + 1} \right)^2 \quad (B.3)$$

In (Eq.B.2), ϕ_e is the power emitted by each luminophores, n_t is the density of luminophore per unit volume on LC (assuming it as uniform), α is the propagation loss coefficient, d is the average propagation distance i.e. the average distance travelled by photon inside the LC, R is the reflection on the back mirror and θ_{max} is the maximum angle for the rays collected within the LC. Moreover, P_2 represents the power of rays which firstly travelled towards the back mirror and propagate towards the output face after reflecting from the back mirror, which can be expressed as:

$$P_2 = R \frac{n_t S \phi_e}{2\alpha \ln(\cos \theta_{max})} (1 - (\cos \theta_{max}))^2 e^{-2\alpha d} (e^{-\alpha d} - 1) \quad (B.4)$$

The total power incident on the output aperture of 3D LC, P_{3D} is calculated using Eq.(B.5) as:

$$P_{3D} = \frac{1}{r} (P_1 + P_2) \frac{T_{Fresnel}}{1 - e^{-2\alpha d} \left(\frac{1 - T_{Fresnel}}{r} R + \left(1 - \frac{1}{r}\right) R^2 \right)} \quad (B.5)$$

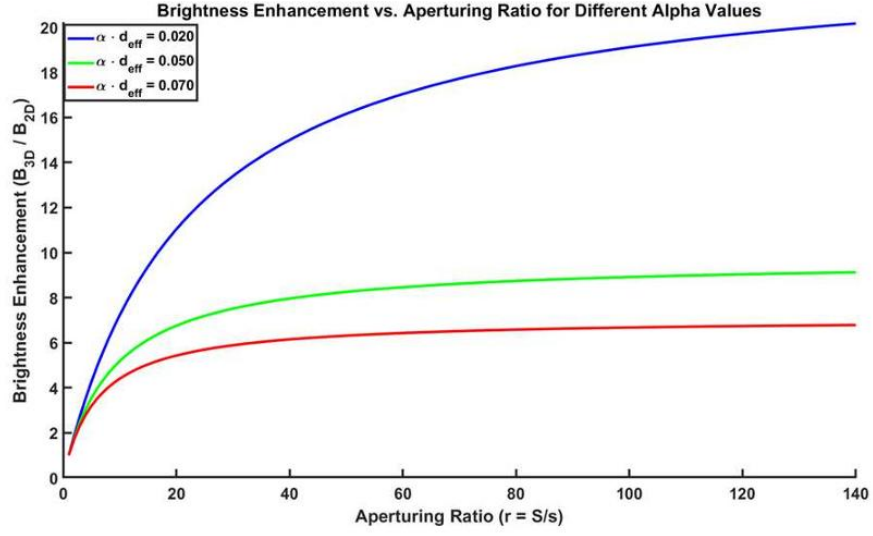


Fig.B.3. (a) Theoretical brightness enhancement calculated using (3) and (6) for different αd values for Ce:YAG.

Brightness enhancement of a 3D LC can be calculated using (Eq.A.B.6) derived analytically in [202]. 3D brightness enhancement is obtained by partially closing the output face with reflective mirrors and leaving a small area for travelling light from LC to outside. In (Eq.B.6), B_{3D} and B_{2D} are the brightness measured at the output face of 3D and 2D LC, respectively, T_{Fresnel} is the transmission of output surface (see (Eq.B.3)).

$$\frac{B_{3D}}{B_{2D}} = \frac{1 - e^{-2\alpha d} R (1 - T_{\text{Fresnel}})}{1 - e^{-2\alpha d} R \left(\frac{1 - T_{\text{Fresnel}}}{r} R + \left(1 - \frac{1}{r}\right) R^2 \right)} \quad (\text{B.6})$$

The reported theoretical brightness enhancement is simulated in Fig.B.3. for different values of αd , for the same cases as in [202]. Fig. B.3. is plotted using Ce:YAG as LC characterised by a refractive index $n = 1.83$. The length (l) of the LC is taken as 100 mm, and the calculated average propagation distance (d) is 109 mm. Mirror reflectivity is chosen as ideal value, 100%, with $T_{\text{Fresnel}} = 0.91$, corresponding to the Ce:YAG-air interface.

Results

In this section we investigated the trade-off between brightness enhancement and power enhancement in Ce:YAG 3D LC. The dimensions of the Ce:YAG LC is chosen for this study as 1 mm thickness (t), 14 mm width (w), and 100 mm length (l). Ce:YAG has refractive index $n = 1.83$ with doping concentration of Ce^{3+} , $n_t = 1.2 \times 10^{22} \text{ mm}^{-3}$. Simulations were performed with different mirrors having different reflectivities. The r is selected from 1 to 140. The optical propagation loss coefficient is taken as 10^{-3} cm^{-1} with $\alpha_d 10^{-2}$ and average propagation distance, (d) is calculated to be 100 mm. Mean path length is 109 and Θ_{max} is 33° as reported in [202]. Here area of the output face $S = 1400 \text{ mm}^2$.

Even though [202] aimed to design light sources combining power, brightness and incoherence using 3D LC by means of light recycling, it inherently includes a trade-off with the total output power, since brightness enhancement and power enhancement are conflicting requirements. How power enhancement is affected by aperturing ratio is shown in Fig.B.4. Power enhancement is the ratio of total output power emitted by 3D LC (P_{3D}) compared to the total output power emitted by 2D LC (P_{2D}). or simply P_{3D}/P_{2D} .

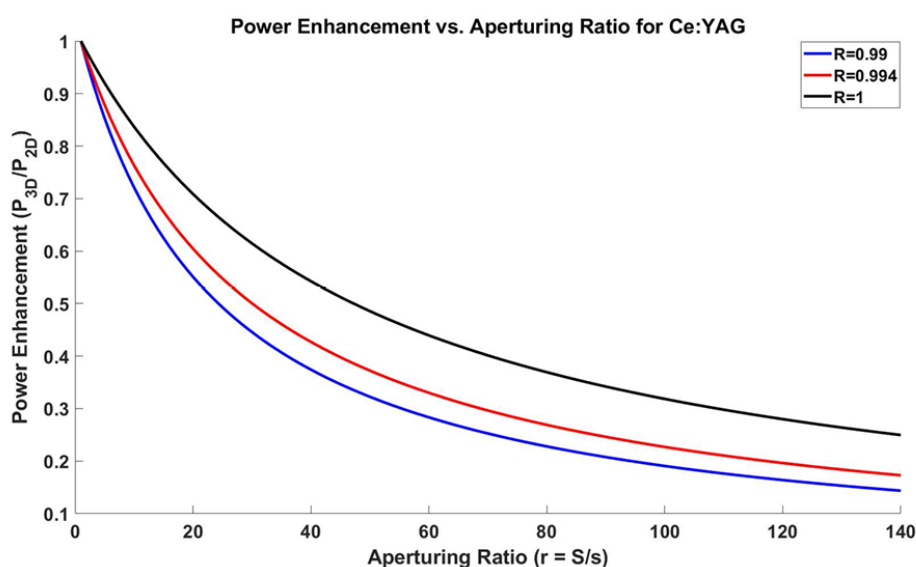


Fig.B.4. Power enhancement vs aperturing ratio for different mirror reflectivity (R).

From Fig.B.4, clearly the power enhancement is decreasing with aperturing ratio because of the $1/r$ factor in the P3D formula. When there is a small aperture, emitted rays from the luminophore forces to undergo multiple internal reflection before escaping through the aperture. Smaller apertures always favour photon recycling inside the 3D LC, which extends the internal travel distance of the emitted light. Longer paths amplify the optical loss due to scattering, mirror reflections, Fresnel reflections, and self- absorption effects. Hence there will be a significant reduction in the total emitted power.

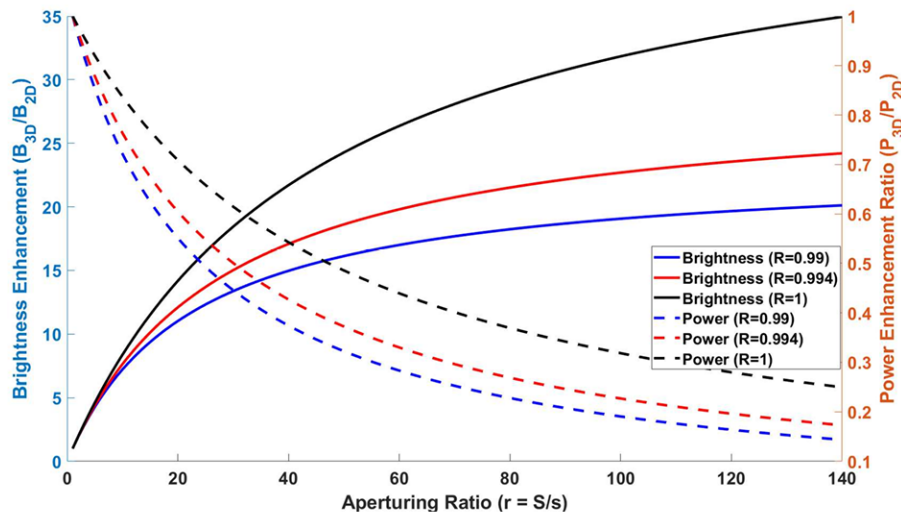


Fig. B.5. Both brightness enhancement and power enhancement vs different aperturing ratios.

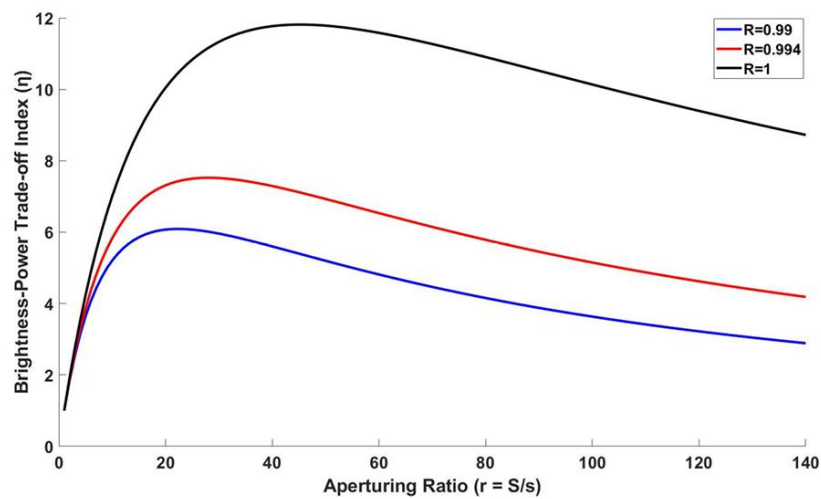


Fig. B.6. Brightness-power trade-off index vs different aperturing ratios.

At lower values of r power is maximized and brightness remains at minimum. Conversely, significant brightness enhancement is achieved for extremely higher values of r where heavy power penalties occur. Fig.B.5 concretizes this inverse proportionality between brightness enhancement and power enhancement and, from Fig.B.5, it is also clear that reflectivity R always favors both brightness and power enhancement. It is evident that the brightness and power enhancement are two conflicting requirements, so there should be a unified approach for balancing these two requirements. Here we propose a new parameter called brightness-power trade-off index (BPTI), η :

$$\eta = \left(\frac{B_{3D}}{B_{2D}} \right) \left(\frac{P_{3D}}{P_{2D}} \right) \quad (\text{B.7})$$

The parameter η considers both the increase in the brightness per unit area and the corresponding power efficiency simultaneously, offering clear guidance of practical design of 3D LC. High value of η of LC indicates where the LC delivers substantial brightness without significant power loss. From Fig. B.6 it is observable that the optimal aperturing ratio, which maximizes BPTI (η), shifts to higher values as the mirror reflectivity R increases. This happens due to the improved photon confinement inside the LC, which favors greater photon recycling with minimal power loss. Consequently, the system can tolerate higher r while still maintaining a better balance between brightness and power enhancement. This behavior leads to the conclusion that for applications requiring higher brightness, using mirror with higher reflectivity, R allows more geometrical freedom without any significant power loss. A clearer version of the above observation is shown in Fig. B.7.

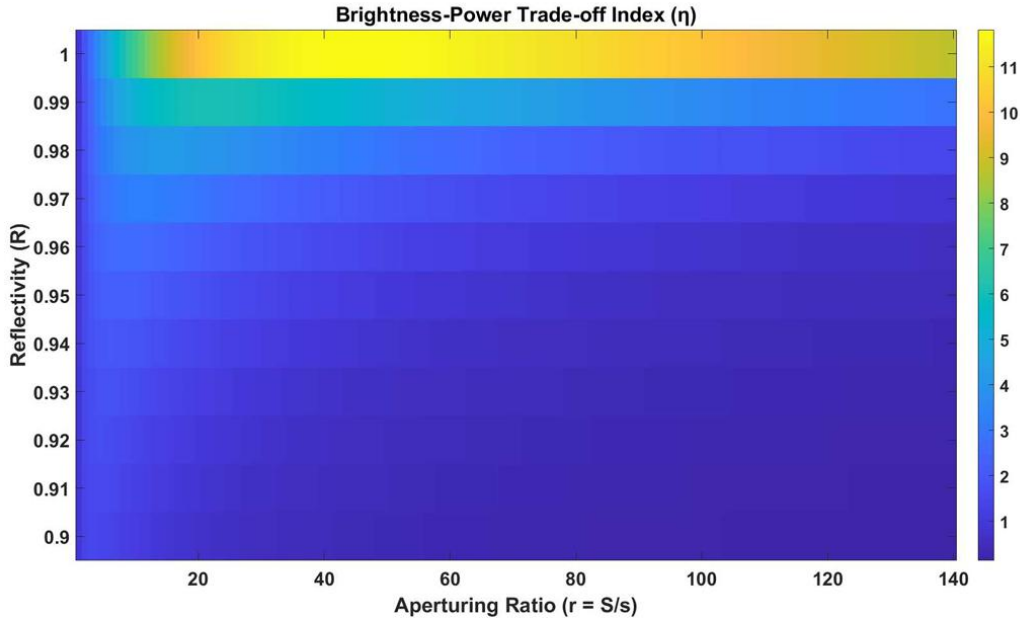


Fig. B.7. *Brightness-power trade-off index heat map with different reflectivity and different aperturing ratio.*

Discussion

This study demonstrates that the brightness enhancement and power enhancement in 3D luminescent concentrators are two opposing mechanisms. Enhancement in the brightness occurs as the aperture size reduces due to the improved photon confinement and increased optical path length. However, the decrement in the aperture size leads to the reduction in emitted power as the photons undergo multiple reflections, which boosts the scattering, Fresnel reflection and reabsorption losses.

The proposed parameter, brightness-power trade-off index, evaluates the trade-off between power and brightness enhancement and quantifies the balance between them. The results show that the brightness power trade-off index helps to find optimal aperturing ratio (aperturing ratio with higher brightness power trade-off index), which will be helpful while designing systems in applications requiring higher brightness without significant power loss. For optimal results mirrors with very high reflectivity, $R \geq 99.4\%$, are recommended.

In conclusion, this work analyses the inverse proportional relationship between power enhancement and brightness enhancement in Ce:YAG 3D luminescent concentrator. We introduced a new parameter called Brightness-Power Trade off Index, which will give the idea about the performance of 3D luminescent concentrator. Also our findings points that higher mirror reflectivity allows for better brightness enhancement at comparably larger aperturing ratios without significantly sacrificing output power, which will offer greater design flexibility. These findings pave the way for developing light source which can deliver significant brightness without compromising power up to an extent, which will be useful in fields requiring advanced lighting, imaging and laser pumping system.

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