Chapter I

INTRODUCTION

1.1. INTRODUCTION

In an antenna array, the radiation of all the antenna elements vectorially sum up, to form the beam in the direction of maximum radiation, which has high gain, high directivity and reduced losses. Additionally, high gain provided by antenna arrays are advantageous for identifying and tracking distant and diminished targets, alongside minimizing sidelobe interference from other directions [1]. Phased Array Antenna (PAA) is a special case of antenna array, where the radiating elements are arranged in a specific pattern and the magnitude and phase of the excitation signal present at each antenna element is modulated in a way to achieve scanning of the main beam in the desired direction which is generally electronically controlled. PAAs are essential for applications such as fast detection in radars, point to point communications and satellite systems, due to their ability to steer beams with high gain and precision. [2]. Some requirements are desired for realization of antenna arrays for PAAs to achieve optimal performance *viz.* wideband, reduced mutual coupling between the radiating elements, power efficient beam steering and an effective phase shifting technique which is discussed in brief.

Wide bandwidth of operation

One of the inevitable features of a Phased Array Antenna (PAA) is the beam steering at a constant angle across the whole visible range of antenna array, thus making the steering independent of the distance [3]. This range-independent beam steering presents difficulties in mitigating Electronic Countermeasure (ECM) signals that arise at the same angular direction but are located at varying ranges from the desired targets. The presence of other frequency channels in the band can help in instantaneously relocating the information bearing signal's frequency to some other frequencies in vicinity. Further, the relocation can minimize the likelihood of detection and intensify difficulties for effective jamming [4]. Current state-of-art approach towards developing wide band antenna element includes Vivaldi, dipole and cavity backed antenna [5-11]. Large aperture antenna arrays generally require complex deployment mechanism which necessitates the antenna elements to be light weighted and low profiled. Planar patch antennas are preferred in array systems because of lightweight, compact form factor, simple fabrication procedure, ease of altering their topology, and seamless integration with other components [10-11]. Patch antennas, however, are often limited by their low impedance bandwidth of ~ 2% [12]. Prior works carried out to enhance the bandwidth of the patch antenna, such as those in [13–22], led to increase in profile and complex designs that are unsuitable for array applications, where the inter-element spacing is kept small to avoid grating lobes. Inclusion of slots in patch geometry lengthen the current path, providing extra resonance, which conjointly with the antenna's principal resonance increases bandwidth of the patch antenna. Another preferred approaches to enhance bandwidth are either by employing cavity back patch or engraving slots on the radiating edge. Cavity-backed patch antenna elements do have superior performance in terms of bandwidth [23], however, at higher frequencies as the array form factor decreases, the construction of cavity-backed antennas can become increasingly intricate and time-intensive and often requires advanced Computer Numerical Control (CNC) machining [24]. Incorporating slots, nevertheless, improves bandwidth without effecting the overall form factor [25]. Substrate Integrated Waveguide (SIW) structures are more compatible with tile-based active phased array architectures, offering advantages such as straightforward implementation, rapid prototyping, and precise fabrication [26]. This makes them a promising candidate for designing a low-profiled, tile-based antenna array systems. The SIW technique effectively emulates a hollow waveguide environment beneath the patch, eliminating the need for bulky metallic cavities. It has been widely utilized to address the narrow impedance bandwidth typically associated with patch antennas in references [27-29]. SIW technology has also been used to supress surface waves thereby improving isolation between antennas in array. [30].

Mutual coupling in compact array systems

Airborne and maritime applications, such as aircrafts, drones, satellites, ships etc., desires minimizing weight and size of the PAA radars which in lieu will enhance fuel efficiency and maximize payload capacity, along with reducing visibility of the radar. In ground based vehicular radar applications, a PAA with lower form factor can easily be integrated within the vehicle’s design. Overall, a compact, lightweight antenna array designs simplify installation and maintenance across all the platforms, enabling faster deployment and enhanced operational agility. Lower form factor of antenna arrays limits space for accommodating large number of antennas leading to minimization of inter-elemental spacing. Reducing interelement spacing to less than half a wavelength of the operating frequency can significantly increase the mutual coupling between the array elements and thus can greatly hamper array performance, mainly effecting its cross-polar radiation characteristics and introducing non-uniformity in gain [31]. The coupling of radiations from the surrounding antenna elements can further introduce changes in the input port impedances consequently effecting the active reflection coefficient of each radiating element and hence, the scanning capability of the array [32]. Active reflection coefficient, Γ_m for the m^{th} element in the array of a $N \times N$ matrix, is given by [33]

$$|\Gamma_m| = \frac{V_m^-}{V_m^+} = e^{jkmd\ \sin\theta_o} \sum_{n=1}^{N} S_{mn} e^{-jnd\ \sin\theta_o} \qquad (1.1)$$

where, V_m^- and V_m^+ are the incident and reflected voltage wave amplitudes at the m^{th} element and θ_o is the scan angle, k is the wavevector and d is the spacing between the antenna elements in the array. As obvious from Equation 1.1, the active reflection coefficient increases with the scan angle. Generally, any compromise on scanning range is unsolicited. Another term which could be manipulated to reduce the active reflection coefficient is the scattering matrix, S_{mn}. The matrix represents the extent of coupling between the elements when $m \neq n$. Ideally, if $S_{mn} = 0$ i.e. no mutual coupling occurs for all $m \neq n$, then Γ_m can be minimized. In practice, it is not possible to obtain zero mutual coupling in an array environment. Additionally, for a compact array environment the spacing between elements further decreases and extent of coupling and hence, S_{mn} becomes more pronounced.

Another important parameter which influences the performance of the array is the active element pattern. The pattern is obtained by activating a single radiating element of an array, while ensuring all the other elements are properly matched, as illustrated in Figure 1.1. The resulting co- and cross-polarization patterns differ from those of an isolated element pattern due to the presence of mutual coupling. The unwanted inter-elemental leakages of radiations to the neighboring elements reduces the gain of each element pattern, consequently affecting the overall gain of the PAA [33-35].

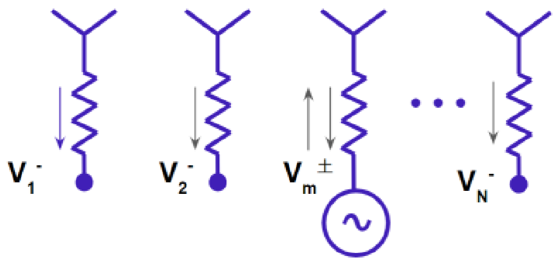

Figure 1.1. Schematic of N element array with only one element excited and rest terminated with matched load taken from reference [32]

Some of the common reported techniques employed for mutual coupling reduction are - combination of shorting pins and conducting wall, neutralization line, electromagnetic band gap (EBG) structures, modifications of ground plane, waveguide metamaterials and metasurfaces. Shorting post, when appropriately placed beneath the patch along with an electrical wall in between the antenna elements, decreases mutual coupling in both E- and H-planes respectively as reported in [36], without any shift in the resonant frequency. On contrary, this technique adds to fabrication complexity and cost, particularly when implemented for large arrays. In references [37-39], current carrying paths are artificially created by adding neutralization line on the antenna surface. The current paths through space and neutralizing lines are in opposite directions resulting in cancellation and as a result mutual coupling reduces. Nevertheless, additional space is required in the array to host the neutralizing line which is undesirable for a compact system. The presence of lines also give rise to multiple coupling paths between adjacent antenna elements in a large arrays and the coupling mechanism becomes complicated.

Another decoupling technique mentioned in [40-42] is using EBG structures, where multiple metal structures having band stop property in the desired frequency range are placed in between the antenna elements. The band stop properties of EBG structure inhibits the propagation of surface waves to neighboring antenna elements, hence lowering the coupling. For closely spaced antenna elements, the inter-elemental spacing is generally $< 0.5\lambda_o$, the technique becomes practically less achievable, limiting its incorporation in compact arrays. Defected ground plane technique has been proposed to reduce mutual coupling in references [43-45]. These techniques require larger inter-element distances and the fallout is increased back lobe radiation. In reference [44], machine learning algorithms are used to leverage coupling among the elements and the design algorithms are complex to implement.

Waveguide metamaterials technique**,** as stated in reference [46]**,** increases cross-polarization levels. Recently, artificially engineered metasurface with left-handed properties viz. periodic split ring resonators [47], pairs of nonuniform cut wires with different lengths [48], two square ring slots [49] and double negative metamaterial (DNG) [50], are developed as superstrate for increasing the inter-elemental isolation. Placement of the metasurface above the array system often results in impedance mismatch between the antenna and the free space. Modifications in the antenna geometry is required for proper impedance matching. All the decoupling techniques mentioned above, till now, requires

modifications in the original design of the antenna elements pre/post fabrication.
To best knowledge of the author, the techniques are tested only for two antenna systems and their effect on large antenna array is yet to be analyzed.

Power efficient beam steering in arrays

Antennas with beam steering capabilities plays a pivotal role in tracking radars, enabling precise detection, monitoring, and tracking of moving targets. Unlike traditional mechanically steered antennas, phased array antenna (PAA) use electronic techniques to steer the radar beam rapidly across different directions without the need for physical movement [51]. This capability allows real-time tracking of fast-moving objects and dynamic adjustment of the beam direction, providing a significant advantage in accuracy and response time.

In PAAs, beam scanning is generally achieved by means of progressive phase shift in the adjacent elements which assists in tilting the beam in the desired direction [52]. The progressive phase shift is realized by phase shifters ingrained in transmit and receive (T/R) modules. These T/R modules are capable of providing fast and accurate phase shifts, however, come with some shortcomings related with their design complexity, cost, weight, power consumption, thermal dissipation and placement constraints [53-55]. Alternative beam-steering techniques like, parasitic patches [56-57], tunable ground plane [58], shorting pins [59-60], metamaterial superstrate [61-65] etc. can be employed instead to alter the beam direction. Out of the various reported techniques, beam steering using superstrate turns out to be more appropriate, as it does not involve any alteration to the antenna design and placement within the array system. A phase shifting surface (PSS) based metasurface printed on the dielectric substrate is used as a superstrate in reference [61]. Mechanically rotating or shifting the position of PSS over the microstrip antenna steers the beam in the elevation plane. A partially reflecting surface with PIN diodes is incorporated as superstrate in a probe fed patch antenna to achieve steering of the beam in [63]. In reference [64], the antenna main beam is continuously steered by mechanically rotating the metasurface superstrate placed above the antenna. A 6-layer frequency selective surface (FSS) is designed incorporated by varactor diodes in reference [66], to steer the beam of a horn antenna. Though, independent beam steering is achieved but the design becomes bulky.

In the discussed approaches, where beam steering is attained using a metamaterial superstrate, either many active elements are employed, or mechanical actuation of the superstrate is required which makes the overall system sizable. Both the steering methods result in high power consumption. A lower power consuming fluidic programmable metasurface superstrate is presented in [67]. Here, the main beam is steered in elevation plane by changing the flow of liquid in the fluidic channels. Nevertheless, the response is slow.

A need for low powered and compact technique for beam steering in antenna array still exists.

Phase reconfiguration technique

Radio frequency (RF) phase shifter (active/passive), is a device capable of changing the transmission phase of an input signal via a control element. RF phase shifters are important components in modern radio frequency systems, enabling dynamic control over the phase of an electromagnetic signals. Traditionally employed in phased array antennas for beam steering, these devices are now gaining increasing relevance in frequency reconfigurability in filters, harmonic distortion cancellation, signal processing, wireless sensing, etc [68-70]. Precise and continuous tuning in phase shifters are often realized either by incorporating mechanical controls [71], MEMS [72-73], varactor-based phase shifter [74-75], or by loading stubs on transmission lines [76]. MEMS technology has turned out to give significant phase shift and are highly compact, nevertheless, the fabrication intricacies are higher in case of MEMS. On the other hand, a time-to-time repair and maintenance is needed for the mechanically controlled parts. Phase shifter with active components are generally fast, accompanied with low insertion loss, but on the hindsight, requires additional dc power accompanied with a complex biasing circuitry [77]. A need for a more reliable, cost-effective and low power consuming tuning mechanism in phase shifters is still the need of the day [78]. Futuristically, features like wide operational bandwidth, low insertion loss, smaller form factor and low power consumption, are to be considered for practical implementation of tunability in phase shifters, which, are often difficult to integrate in a single platform. Fluidic reconfigurability offers a promising solution in terms of simple and cost-effective designs as they are void of mechanical movement, active elements and complex biasing networks. The fluidic flow is often controlled via an external mechanism, hence, do not interfere with the system's power handling capacity [79]. Fluidic channels with fluids like liquid metals [80], dielectric solution like FC-77 [81] have been successfully implemented for phase reconfigurability in phase shifters. These fluids are expensive. In reference [82], low-cost fluids are used to achieve a phase shift upto 50° by altering the capacitance of a printed interdigitated capacitor (IDC) printed on a photo paper. This is accomplished by introducing fluids with different permittivity into a microfluidic channel externally positioned above the printed IDC. The use of photo paper as the substrate and the external placement of the fluidic channels introduce mechanical fragility and limited structural ruggedness, making the design less suitable for robust applications.

A more rugged, mechanically stable, cost-effective and low power consuming phase reconfiguration for potential application in phase shifters, circuits and RF sensors is still the need of the day.

1.2. FORMULATION OF RESEARCH PROBLEM AND OBJECTIVES

The insights from the reviewed literature primarily targets the following design considerations and challenges in antenna arrays:

- **Wide bandwidth and low-profile design:** Electronic Counter-Countermeasures (ECCM) require alternate frequency channels to effectively counter jamming or interference. An alternate frequency channel should be available for quick manoeuvring of operational frequency. Further, a compact and lightweight design with low form factor will facilitate ease of manufacturing, transportation, integration into space-constrained platforms and be less conspicuous. Achieving wide bandwidth and low form factor in patch antenna arrays simultaneously is difficult.
- **Mutual coupling reduction technique in array**: The mutual coupling reduction techniques reported, if incorporated on to a pre-existing array result in modification of antenna design for optimized performance. Any alterations in the element design impedes its implementation and disrupt the integration of the antenna with other electronics and also alter the calibration settings. Hence, there is a need of a simple and easy integrable mutual coupling reduction technique, which does not require any revamping of predesigned antenna array.
- **Active beam steering in antenna array**: So far, active beam-steering in antenna using metasurface is achieved either by using large numbers of active components within the metasurface superstrate or mechanical movement of the metasurface

superstrate, resulting in high costs, sizable mechanisms, and often consuming high power. Most of the reported work aimed in steering the beam are for single antenna. A simple, fast and low powered beam steering technique is required for efficient power-to-performance management in antenna array.

- **Compact, low-cost phase reconfiguration system**: Phase reconfiguration system faces challenges of fabrication, time to time maintenance, high power consumption, prone to external damage etc. There is a need for a robust RF phase tuning mechanism, which at the same time is scalable, have reliable performance across all the RF applications and cost-effective.

Based on the observations, the following **objectives** have been identified:
Development and realization of

A. wideband and small form factor antenna array for phased array antenna applications

B. decoupling technique in compact antenna arrays without reverting to any modifications in original geometry.

C. low-powered and fast beam steering ability for antenna arrays.

D. a robust, compact, low-cost phase reconfiguration technique.

1.3. THESIS STRUCTURE AND OUTLINE

The X-band (8.2 GHz to 12.4 GHz) phased array radar is widely utilized in maritime, aeronautical, and defense communication systems for maritime vessel traffic control, air traffic control, high-resolution tracking of targets, weather monitoring, remote sensing, satellite application, and also recently extended to commercial point-to-point communication systems [83]. Given the broad range of applications and advantages associated with the X-band, all the studies included in this thesis are conducted within the X-band frequency ranges. However, the methodologies and design principles outlined in this work are adaptable and can be applied to other frequency ranges as needed.

The thesis has been arranged into six chapters. The current chapter, with relevant literature, discusses the performance requirements of antenna array for a PAA system and thus formulate the motivation and objectives of this dissertation.

In **Chapter II** a modified E-patch antenna is designed and tested with substrate integrated waveguide technology on a low-profiled substrate for a wide bandwidth performance. Further, a technique of on-board calibration within the same plane of the array is proposed for providing access to in-field calibration.

The effect of mutual coupling is mitigated for closely spaced antennas in an array, by placing a metamaterial-based superstrate. The technique is optimized and tested for 1×3 and 1×7 antenna arrays and detailed in **Chapter III**.

Chapter IV presents a metasurface superstrate-based beam steering technique in antenna array. The metasurface is so designed to incorporate minimum number of active elements for low power consumption.

A robust, compact and cost-effective technique for phase tunability is proposed and tested in **Chapter V**. The design uses in-built fluidic channels for phase tuning.

The thesis concludes in **Chapter VI** which summarizes the work conducted and compares the outcomes with similar state-of-the-art work. A discussion is included which evaluates future perspective to the work conducted.

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