CHAPTER VI

ACHIEVEMENTS AND FUTURE DIRECTIONS

Electronic beam forming in phased array antennas have a distinct advantage over the mechanically steered antennas by achieving a rapid and precise control over the direction of the transmitted or received signal. In many real-world usages, a large number of antenna elements are essential to increase the achievable gain, which results in either using a large size and overly weighted array aperture or a large numbers of closely packed antenna elements leading to inter elemental interference. There are certain application scenarios which desires a broad bandwidth, low profile, easy portability and mobility, less power consumption, quick repositioning and a low probability of intercept. The work carried out in this dissertation, addresses some of the solutions to enhancing bandwidth, size, weight, power and inter-elemental interference in antenna arrays to make Phased Array Antennas (PAAs) highly versatile, compact and suitable for a wide range of applications.

Bandwidth of the antenna array has been improved by using slotted E-shaped patch as the fundamental radiating element engraved by surface integrated waveguide(SIW) structure. Calibration lines are printed onboard parallel to the non-radiating edge in between the antenna elements to facilitate an ease for onsite calibration of the array. Here a 64-element array with calibration lines is fabricated and tested for return loss of the center element and its active radiation pattern at 8.75GHz. The developed 64-element SIW integerated antenna array with an inset showing modified E-patch is shown in Figure 6.1.

Quantative performance of the developed array is compiled in Table 6.1.

Table 6.1 Quantitative study of the center element of the 8 × 8 array

Antenna	Bandwidth (%)	Beamwidth (°)		Cross-polarization levels (dB)		Scanning volume		Gain (dB)	Efficiency (%)
8×8 array	7.95	E-plane	H-plane	E-plane	H-plane	E-plane	H-plane	4.82	80.41
		104.1	112.09	23.51	23.1	±60°	±50°		

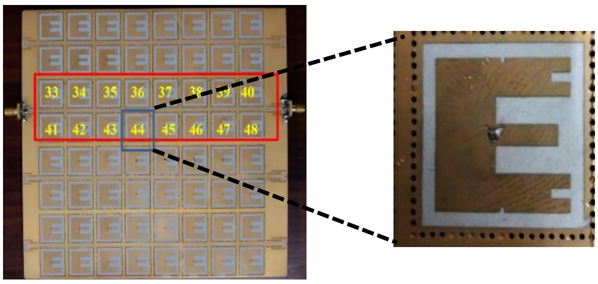


Figure 6.1 8×8 SIW integrated E-shaped patch antenna array.

Table 6.2 illustrates the state-of-the-art to other wideband low-profiled antenna array.

Table 6.2 Comparison to other reported literature using cavity type approach for low-profiled and wideband antenna array in terms of bandwidth (BW), antenna size, bandwidth, profile and technique applied.

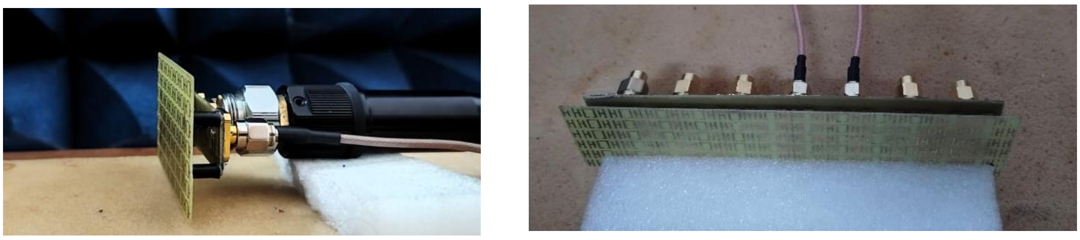
Reference	Approach	Antenna size	BW (%)	Height (λ_o)
[1]	Air cavity	$1.26\lambda_o \times 1.26\lambda_o$ at 18 GHz	21.50	0.53
[2]	SIW cavity	-	12	0.11
[3]	SIW cavity	$0.50\lambda_o \times 0.56\lambda_o$ at 16.8 GHz	16.07	0.13
[4]	SIW Cavity	$1.3\lambda_o \times 1.3\lambda_o$ at 14GHz	5.7	0.03
[5]	SIW Cavity	$0.66\lambda_o \times 0.79\lambda_o$ at 10 GHz	1.7	0.02
Proposed work	**SIW cavity**	**$0.51\lambda_o \times 0.49\lambda_o$ at 8.75GHz**	**7.95**	**0.03**

The proposed single antenna element in the array is very compact and low profiled with sufficiently good bandwidth. Thus can be extended to make large active array antenna structures where wide bandwidth with low-profile is of importance, by stacking up in *x* or *y* directions in a planar grid arrangement.

Another aspect which was taken in the work is reducing interelemental interference in a compact array system. A single-layer, low-profile metasurface superstrate (MS) is placed above the array to mitigate mutual coupling. This approach needs no modifications in parent antenna design. The configuration achieves mutual coupling levels as low as -25 dB for both 1×3 and 1×7 antenna array array setup. The performance parameters at 8.3GHz are listed in Table 6.3. The developed prototype of the MS and antenna array is shown in Figures 6.2(a-b).

Table 6.3 Performance of the 1×3 antenna array without (WO) and with (W) metasurface at 8.3GHz

Excitation mode	Bandwidth (%)	Mutual coupling @ 8.3GHz (dB)		Gain (dB)	Active cross polarization (dB)	
		Simulated	Measured		H –plane	E -plane
Center element - WO metasurface	3.11	-19.10	-20.47	2.36	16.61	23
Center element- W metasurface	**5.12**	**-32.43**	**-31.02**	**3.2**	**34.46**	**31**



(a) (b)

Figure 6.2 Proposed metasurface for mitigating mutual coupling in closed spaced (a) 1×3 and (b) 1×7 patch antenna array.

A comparison of the work with some similar work on mutual coupling reduction in antenna array using metasurface superstrate is presented in Table 6.4.

Table 6.4 State-of-the-art mutual coupling reduction techniques in antenna array employing metasurface superstrate technique in terms of bandwidth, profile, spacing between the antenna elements, improvement in isolation levels and wether any smodification required if any in parent antenna design .

Ref.	*Method*	*Array size*	*Bandwidth*	*Profile*	*Spacing*	*Isolation (dB) #*	*Alteration ##*
[6]	Superstrate	1×2	400 MHz	0.09 λ_o	0.02 λ_o at 5.8 GHz	30	Yes
[7]	Superstrate	1×2	7.69% & 5.88%	0.14λ_L	0.008λ_L	26	Yes
[8]	Superstrate	1×2	1.7% and 3.46%	0.21λ_L	0.06 λ_L	23	Yes
[9]	Superstrate	1×2	3.86%	0.22λ_o	0.095 λ_o	10	No
This work	**Superstrate**	**1×3**	**5.12%**	**0.31λ_o**	**0.15 λ_o at 8.3 GHz**	**14.37dB**	**No**
		1×7	**4.48%**			**9.2dB**	

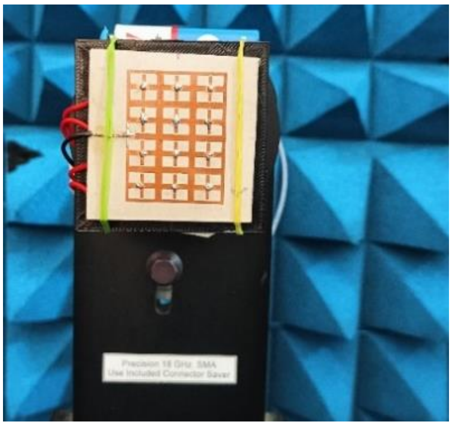
 # Improved isolation, ## Alteration in antenna structure required post placement of superstrate. λ_L is the free space wavelength at lower resonant frequency and λ_o is the free space wavelength at the center resonant frequency.

The proposed method does not require any alteration in parent antenna array geometry after incorporating the metasurface superstrate above the antenna array after incorporation of the metasurface superstrate, making it particularly suitable for large antenna array applications. Furthermore, the approach is scalable and can be easily adapted to larger linear arrays simply by optimizing the superstrate's placement height.

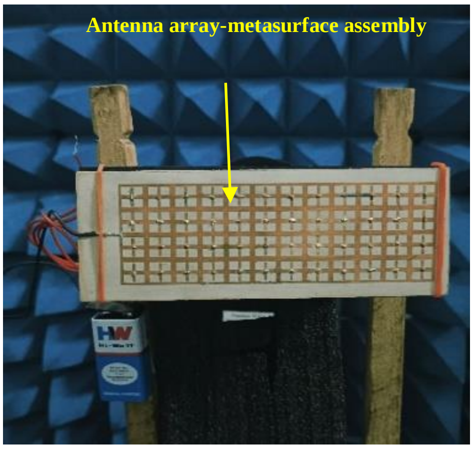
A noticeable enhancement in bandwidth is observed without much compromise to the overall profile of the system.

Beam steering in antenna array is mainly accomplished using expensive and high powered T/R modules or otherwise uses complex electronics or mechanical actuation techniques . A low-powered and easily manufactured transmission phase reconfigurable metasurface superstrate (MS) based technique is used for beam steering in unit antenna and 1×4 array as shown in Figures 6.3(a-b). Phase tunning capability is realised by changing the operation state of one PIN diodes placed strategically in the MS unit cell. In terms of single antenna, the metasurface is able to steer in the direction of the main beam upto $\pm 27°$ in $\phi = 90°$ plane giving a total scan volume of 54°. The technique is further verified in 1×4 antenna array, where the single antenna was multiplied to form 1×4 antenna array. In this configuration the MS is able to steer the beam of the antenna array to $\pm 27°$, giving a scan volume of 54°. The biasing scheme of the PIN diodes is simple using a single voltage applied at the edges of the MS to control all the PIN diodes simultaneously. The diodes are arranged in a redundant network, to ensure that even if some of the diodes experience variations in their DC resistance or fails, the overall functionality remains unaffected. Reference frequency of 10GHz is taken for the study.

A comparison of the proposed technique with already existing technology in terms of beam steering in patch antenna using metasurface superstrate is presented in Table 6.5.



(a)



(b)

Figure 6.3 Developed prototype of metasurface superstrate on (a) single and (b) 1×4 patch antenna array radiation pattern measurement setup.

Table 6.5 State-of-the-art literature using metasurface superstrate for beam steering in patch antenna.

Reference	**Antenna topology**	**Technique**	**Beam steering**	**Number of active elements**
[10]	Array (1×2)	Electronically	±15°	72
[11]	Single	Electronically	±17°	36
[12]	Single	Electronically	±22°	72
[13]	Single	Mechanically	±30°	-
[14]	Single	Fluidic	±20°	-
This work	**Single**	**Electronically**	**±27°**	**12**
	1×4 antenna array	**Eletronically**	**±27°**	**48**

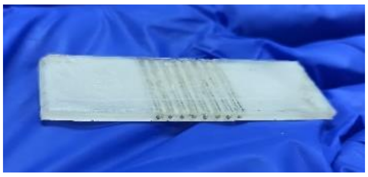
The proposed metasurface based superstrate technique is capable of steering the beam of 1×4 antenna array without effecting its resonance frequency. The technique is low-powered uses a very less number of active elements which is two-third of the amount used in [10] for beam steering 1×2 antenna array. Furthermore, the method doesnot involve any alteration to the original antenna design and placement.

A fluidic-based dynamic phase reconfiguration approach is proposed for X-band applications. Fluidic channels are directly incorporated in an epoxy layer sandwiched between the two coupled microstrip structures. This insitu placement of the fluidic channels makes the technique unobtrusive, simplifies the fabrication and provides a self-shield to the channels from any external damage. No external biasing circuitry and active components are required making the implementation economical and low in power consumption. DI water is used as a tuning fluid to achieve a continuous and controllable phase shift. A maximum phase shift of 43.8°, which is achieved in 5 discrete phase states with insertion loss ranging from -2.65 dB to -4.92 dB. The phase changes are revertible and is accomplished by simply de-flushing the fluids from the channels. Table 6.3 compares the present work with available literatures on fluidic based phase reconfiguration in terms of performance and technology used for manufacturing. The developed prototype is shown in Figures 6.4(a-b).

Table 6.6 Comparison of the proposed design with existing works on fluidic phase reconfiguration

Ref.	f_{opr}	$\Delta\phi_{max}$	*IL* (dB)	*BW* (GHz)	Technology/Placement	Fluids used
[15]	900 MHz	52°	-4 dB to -5.6dB	~0.6	PMMA micromachining CPW/	DI water, Ethanol, Hexanol and Air.
[16]	6 GHz	86°	< -10dB	--	3D printing Microstrip	Air, Ethanol, Methanol, Toluene, Water
[17]	1.84 GHz	94°	-1.75 dB to -3 dB	3	CPW with PDMS microfluidic channel / On top of glass wafer Borofloat33	DI water
Proposed Work	10.5GHz	43.8°	-2.65dB to -4.92dB	~2.3	Insitu and unobtrusive Fluidic channels in epoxy substrate	DI water
#PDMS- Polydimethylsiloxane, PMMA- Polymethyl methacrylate, CPW-Coplanar Waveguide; DI- Distilled ionized, f_{opr}-operational frequency, $\Delta\phi_{max}$- maximum phase shift, IL – Insertion Loss, BW- Band width.						

The technique excludes inclusion of any external biasing circuitry and active components, hence simple and low-powered. The placement of the fluidic channels makes the fabrication simple, unobtrusive and shields the fluidic channels from any external damage, unlike [15], where the fluidic channel is exposed making it more prone to external damage. Most of the reported techniques are developed for lower frequencies and hardly any work for higher microwave frequencies have been reported. The correlation between the fluid permittivity and the observed phase response highlights the potential of the proposed structure to function not only in RF circuits but also as a RF sensor for fluid quality monitoring.



(a)

(b)

Figure 6.4 Developed prototype of (a) Fluidic channels incorporated in epoxy substrate and (b) fluidic channel based vertically slot-coupled microstrip structure for phase reconfiguration.

Highpoints of the work

- A wideband (7.95%) single antenna element is developed with a profile as low as $0.03\lambda_0$ where λ_0 is the free space wavelength at 8.75GHz. The single element is used to develop a 8×8 array with a wide scanning capability.
- Calibration lines are printed on board the array to facilitate in-field calibration feature.
- A metasurface superstrate based mutual coupling reduction technique is demonstrated and verified for closesly spaced antenna in 1×3 and 1×7 antenna array settings. Simply optimizing the position of superstrate an improved isolation of 14.37dB and 9.2dB is achieved.
- The decoupling technique proposed in this thesis doesnot require any modification in the parent antenna design in the array, which verifies that the metasurface doesnot hinder with the antenna array's impedance conditions. These findings validate the scalability and effectiveness of the proposed metasurface-based mutual coupling reduction technique and an easy transfer of technology to pre-existing antenna arrays.
- A low-powered, metasurface superstrate based electronic beam steering approach is tested and verified for antenna array. A simple and reduntant biasing network is demonstrated for the PIN diodes incorporated in the metasurface for the beam switching of the antenna array. A very less number of PIN diodes have been employed to achieve a maximum scanning volume of $54°$ is achieved in 1×4 antenna array.
- A robust fluidic based phase reconfigurable design in demonstrated and verified. The technique uses a vertically coupled microstrip structure enabling a phase tuning of $43.8°$ using a low-cost and easily available distilled (DI) water as a tuning fluid in the fluidic channels.
- The proposed work has a potential application not only in reconfigurable RF filters and circuits, phase shifters, structural health monitoring (SHM) but also can be used as a RF fluid quality monitoring system.

Future directions

The present study exhibited a technique for mitigating mutual coupling suitable for linear patch antenna array without any modification in parent antenna design. The efficacy of the technique is still to be explored for planar antenna array where the mutal coupling can occur in both the orthogonal planes. Research on metasurface configurations that maintain mutual coupling reduction performance under dual-polarized or circularly polarized operation without any alteration to parent antenna design can be emphasized.

The low powered beam steering technique is proposed for patch antenna arrays only. For real-time applications and higher 5G communication, where precise tracking of targets is required, antenna array with finer beam steering resolution will be required. Resolution of the beam can be further increased by improvising the metasurface design to achieve more phase states per unit cell or developing a programmable biasing matrix to control the operating state of the unit cells independently. This could be a challenging and interesting work.

The present study is confined to a linearly polarized, basic patch antenna array configuration. However, for specific phased array applications, polarization-independent and broadband antenna designs are more suitable. The adaptability of the proposed techniques can be investigated.

A technique of low-cost and low-powered phase reconfiguration is presented. However, study on further increasing the phase change volume can be considered by incorporating multi-layer structure that can accommodate more number of fluidic channels. Integrating the proposed proof of concept into a real time RF sensor for fluid quality monitoring can be an area of future research.

Although the study is focussed on applications in X-band region. Expanding the techniques to cover higher frequency bands could be an intriguit area of future work.

The work carried out in this thesis has successfully found solutions to low-profiled wideband array, reduction of mutual coupling by simultaneously preserving the parent antenna design, a low-powered and simple beam steering technique which can be implemented in antenna arrays for PAA applications. Furthermore, a dynamic phase reconfiguration technique for wide RF applications is also presented.

References

[1]. Laha, T., Ram, G., Kumar, G. A., & Chakravarthy, M. Compact wideband slotted E-shaped patch antenna for Ku-band phased array applications. *IEEE Transactions on Aerospace and Electronic Systems*, **2024**: 1–11.

[2]. Awida, M. H., Kamel, A., & Fathy, A. E. Analysis and design of wide-scan angle wide-band phased arrays of substrate-integrated cavity-backed patches. *IEEE Transactions on Antennas and Propagation*, 61(6): 3034–3041, 2013.

[3]. Li, H., Qing, A., Xu, Z., Yu, Z., & Zhang, S. Design of physically connected wideband SIW cavity-backed patch antenna for wide-angle scanning phased arrays. *IEEE Antennas and Wireless Propagation Letters*, 20(3): 406–410, 2021.

[4]. Heydarzadeh, F., & Neshati, M. H. Design and development of a wideband SIW-based cavity-backed slot antenna using two symmetrical circular corner perturbations. *International Journal of RF and Microwave Computer-Aided Engineering*, 28: 21552, 2018.

[5]. Luo, G. Q., Hu, Z. F., Dong, L. X., & Sun, L. L. Planar slot antenna backed by substrate integrated waveguide cavity. *IEEE Antennas and Wireless Propagation Letters*, 7: 235–239, 2008.

[6]. Wang, Z., Zhao, L., Cai, Y., Zheng, S., & Yin, Y. A Meta-Surface Antenna Array Decoupling (MAAD) Method for Mutual Coupling Reduction in a MIMO Antenna System. *Scientific Reports*, 8(1), 2018. https://doi.org/10.1038/s41598-018-21619-z

[7]. Liu, F., Guo, J., Zhao, L., Huang, G. -L., Li, Y., & Yin, Y. Dual-Band Metasurface-Based Decoupling Method for Two Closely Packed Dual-Band Antennas. *IEEE Transactions on Antennas and Propagation*, 68(1): 552–557, 2020. https://doi.org/10.1109/TAP.2019.2940316

[8]. Li, M., Mei, J., Yang, X., Zeng, D., & Yi, Z. Isolation enhancement based on Metasurface for Dual-Band E/H-Plane coupled antenna array. *IEEE Antennas and Wireless Propagation Letters*, 2024: 1–5. https://doi.org/10.1109/LAWP.2024.3386677

[9]. Mark, R., Rajak, N., Mandal, K., & Das, S. Metamaterial based superstrate towards the isolation and gain enhancement of MIMO antenna for WLAN application. *AEU - International Journal of Electronics and Communications*, 100: 144–152, 2019. https://doi.org/10.1016/j.aeue.2019.01.011

[10]. Ji, L., Guo, Y. J., Qin, P., Gong, S., & Mittra, R. A reconfigurable partially reflective surface (PRS) antenna for beam steering. *IEEE Transactions on Antennas and Propagation*, 63(6): 2387–2395, 2015. https://doi.org/10.1109/TAP.2015.2412143

[11]. Ji, L., Fu, S., Zhang, L., & Li, J. One-dimensional beam-steering Fabry–Perot cavity (FPC) antenna with a reconfigurable superstrate. *International Journal of Microwave and Wireless Technologies*, 12(3): 233–239, 2019. https://doi.org/10.1017/S1759078719001144

[12]. Ji, L., Zhang, Z., & Liu, N. A Two-Dimensional Beam-Steering Partially Reflective Surface (PRS) antenna using a reconfigurable FSS structure. *IEEE Antennas and Wireless Propagation Letters*, 18(6): 1076–1080, 2019. https://doi.org/10.1109/LAWP.2019.2907641

[13]. Das, P., Mandal, K., & Lalbakhsh, A. Beam-steering of microstrip antenna using single-layer FSS based phase-shifting surface. *International Journal of RF and Microwave Computer-Aided Engineering*, 32(3), 2021. https://doi.org/10.1002/mmce.23033

[14]. Naqvi, A. H., & Lim, S. A Beam-Steering Antenna With a Fluidically Programmable Metasurface. *IEEE Transactions on Antennas and Propagation*, 67(6): 3704–3711, 2019. https://doi.org/10.1109/TAP.2019.2905690

[15]. Choi, S., Su, W., Tentzeris, M. M., & Lim, S. A Novel Fluid-Reconfigurable Advanced and Delayed Phase Line Using Inkjet-Printed Microfluidic Composite Right/Left-Handed Transmission Line. *IEEE Microwave and Wireless Components Letters*, 25(2): 142–144, 2015. https://doi.org/10.1109/LMWC.2014.2382685

[16]. Radonić, V., Birgermajer, S., & Kitić, G. Microfluidic EBG Sensor Based on Phase-Shift Method Realized Using 3D Printing Technology. *Sensors*, 17(4): 892, 2017. https://doi.org/10.3390/s17040892

[17]. Murray, C., & Franklin, R. R. . *Microwave and Optical Technology Letters*, 55: 789–793, 2013.