Chapter 6

Conclusion and Future Scope

This chapter summarizes and concludes the investigation presented in the thesis with the emphasis on the key findings. A scope for the further work on the topic is also discussed in this chapter.

6.1 Summary and Conclusion

The performance of the antenna elements is severely affected due to the high coupling coefficient in the multi-element antenna arrays. The radiation characteristics deteriorate significantly in antenna arrays with closely spaced antenna elements. Moreover, the end-user devices need to be compact and hence, does not provide much space for antennas. Mostly microstrip and printed antennas and their variants are utilized in wireless devices like mobile phone, tablet, wireless access point etc. Because of the strict space constraint in such devices, the antenna elements are poorly coupled with the space wave and surface wave effects. Shorted microstrip antenna and their variants like an inverted-F antenna (IFA) and planar inverted-F antenna (PIFA) are preferred because of the quarter wavelength operation, however, these antenna elements are strongly coupled due to the current in the common ground plane. Moreover, even if the antenna elements are decoupled sufficiently (~15 dB isolation), isolation needs a further improved to avoid the performance degradation of the antenna isolation characteristics under the influence of practical device assembly.

A number of isolation enhancement techniques like defected ground structure (DGS), neutralization line, ground resonator, resonator between radiating elements, metal wall, and their combinations were utilized in the past. However, issues like degradation in radiation patterns, fabrication problem due to the protruded geometries of the decoupling structures, highly resonant nature of the decoupling structure, single band behavior etc. are associated with these many techniques. The isolation enhancement techniques based on metamaterial are emerging nowadays. Planar form of the metamaterial is called metasurface and provide promising features like the ease in fabrication, geometrical tunability, and scalability. The metasurfaces can be designed with the desired reflection, transmission, and absorption characteristics in the frequency band of interest by just varying the geometrical parameters. Such a metamaterial/metasurface based compact ultrathin multiband microwave absorber structures have been investigated in this thesis. The application of such an absorber was explored as an isolator in a four-port multiple-input multiple-output (MIMO) antenna system.

This thesis started with the introduction of the effect of coupling in multi-element antenna systems like antenna array, MIMO antenna, and repeater antenna system presented in chapter 1. The state-of-the-art review of various isolation enhancement techniques along with their pros and cons were presented. Some research gaps were identified based on the literature review that motivated to work towards this thesis. Finally, the scope and structure of the thesis were discussed.

In chapter 2, a compact and ultrathin metamaterial absorber with dual-band absorption characteristics in C- and X- frequency bands were presented. The proposed structure was a three-layered structure in which top and bottom metallic layers were separated by the dielectric substrate. The top layer was an electric resonator constructed of closed ring resonator (CRR) and square patch and these two basic geometries were connected at the diagonals. The proposed structure has peak absorptivities of 95.02% and 99.84% at 4.215 GHz and 10.95 GHz, respectively. The parametric variation was discussed in detail to understand the dependence of absorption frequencies on the design parameters. The factors responsible for achieving high absorption level were also discussed thoroughly. It was observed that the proposed structure supports the realization of near unity absorption at the two absorption frequencies independently by suitably varying the design parameters. Moreover, the proposed structure showed polarization insensitivity owing to its symmetrical geometry. The absorption mechanism was explained with the *E*-field and surface current distribution plots at the peak absorption frequencies. Constitutive electromagnetic parameters of the proposed structure were retrieved and plotted against frequency. A sample of the proposed absorber was fabricated and measured using free space measurement method. The measured response was found in close agreement with the numerical results for the normally and obliquely incident electromagnetic wave. It was observed that the proposed structure worked well up to an angle of incidence of 60^0 and showed wide-angle performance.

The proposed dual-band absorber structure presented in the previous chapter was analyzed using numerical solver and verified experimentally. Numerical solvers provide fast and accurate analysis based on the used meshing criteria. However, to get the good physical insight of the resonance behavior of such structures, equivalent circuit modeling is often desired. Therefore, in chapter 3, an equivalent circuit was proposed using transmission line method (TLM) for the presented dual-band metamaterial absorber. Simulated reflection response was taken as a reference to compare the analytical results. To obtain the equivalent circuit, the frequency selective surface (FSS) forming the absorber top layer was considered as a combination of two simpler FSS. The individual absorbers formed by two such FSS were correctly modeled using TLM. The values of all the lumped capacitances and inductances were calculated and the effect of neighboring unit cells was considered. The effect of the bending in the CRR structure and finite thickness of the metallization was also considered in the equivalent circuit model. The obtained equivalent circuits were combined by incorporating the involved coupling capacitances into the calculation. Involved coupling capacitances have been calculated to get a correct match in the analytical and simulated results. The presented equivalent circuit model would pave the way in getting the good physical insight of the resonance phenomenon of the presented structure.

After numerically, analytically and experimentally investigating the dual-band metamaterial absorber, a variant of the previously proposed resonator was studied to design and develop quad-band metamaterial absorber in chapter 4. Very few absorber structures have been reported with quad-band and more absorption bands in GHz frequency range. It is because of the difficulty in achieving absorption in multiple bands due to the strict conditions of perfect absorption. The proposed unit cell geometry utilized a 2 x 2 array of the variant of electrical resonator presented in chapter 2 in a single unit cell to realize a quad-band absorber. Simulated peak absorptivities of 98.5 %, 97.7 %, 94.8 % and 96 % were obtained at 4.34 GHz, 6.68 GHz, 8.58 GHz, and 10.64 GHz, respectively. All four resonators were oriented perpendicular to each other in a unit cell to achieve symmetrical structure, and hence polarization insensitiveness. The proposed absorber has wide-angle performance. Parametric variation of some key parameters was presented and it was observed that the absorption frequencies can be optimized by varying the geometrical parameters. The E-field and surface current distributions on the proposed absorber unit cell have been studied for getting insight into the absorption mechanism. Measured results have been obtained by the free space measurement method and found in good agreement with the simulated results.

After investigating dual-band and quad-band metamaterial absorbers, its application to decouple antenna elements was explored in chapter 5. A variant of the metasurface geometry presented in previous chapters i.e. a patch enclosed in a CRR and connected to it at the diagonals was employed in this chapter to decouple antenna elements in a four-element MIMO antenna array. The presented four-element MIMO antenna array utilized PIFA as the radiator and the array was designed for 5 GHz WLAN (wireless local area network, band 1: 5.15–5.35 GHz, band 2: 5.725–5.825 GHz) access point applications. Sufficient isolation between antenna elements was obtained utilizing spatial/pattern diversity. To prevent the detrimental effects of the practical device assembly on the antenna isolation characteristics, a metasurface based isolator has been placed between the antenna elements. Parallel (TM) polarized wave incident between the antenna elements was identified as the cause of coupling. Therefore, a solution to decouple the antenna elements was proposed that could absorb the significant power of the parallel polarized wave and reflect the perpendicular (TE) polarized wave as a co-polar reflected wave. As the dissimilar behavior of isolator was required for the TM and TE polarized wave, therefore, an array of asymmetric metasurface unit cell was employed between the antenna elements. The reflection/absorption response of the proposed metasurface has been discussed in detail. The proposed isolator significantly improved the isolation between various antenna pairs. The working mechanism of the proposed isolator was explained with the surface current distribution plot. The effect of the isolator on the radiation pattern, radiation efficiency, and peak realized gain was discussed, and sufficient values were obtained to use the proposed antenna array for indoor applications. Envelope correlation coefficient (ECC) values for all three antenna pairs were well below the standard limit set for wireless communication devices and thus making it suitable for the MIMO application. The diversity capability of the proposed antenna array has been evaluated in terms of apparent and effective diversity gain. The simulated results of the proposed MIMO antenna array have been validated with the experimental results and found in close agreement.

6.2 Scope for Further work

While the main emphasis of this thesis is to design and develop multiband metamaterial absorber and its application for antenna isolation enhancement, the substantial number of future directions are enabled by this thesis. Some of the scopes for the further work are listed as:

i. Broadband compact ultrathin polarization-insensitive wide-angle metamaterial absorber could be designed and utilized for antennas performance enhancement.

ii. The approach of developing an analytical model for the multi-resonator metamaterial absorber geometries could be utilized for analytical modeling of the more complex resonator geometries.

iii. An asymmetric metasurface based isolator with perfect cross-polar conversion for TM polarized wave and co-polar conversion for TE polarized wave could be investigated to prevent deterioration of the antenna efficiency in the presented MIMO configuration.

iv. Development of the switchable metasurface with the above-mentioned characteristics could be beneficial for decoupling the antennas used in cognitive radios.