At the end of this journey, I realise that my path does not end here and extends onto horizon. Applications of metamaterials are opening up more and more. With pleasure I apprehend that ' I have miles to go before I sleep..... '. But, every journey needs a stopover and with my guide’s blessings, I wind up my work at this point to sum up this thesis.
8.1 Thesis Highlights

In chapter 1, study of metamaterials is performed to understand the meaning and nature of this term. Attempt is done to compare different types of metamaterials and keeping in mind, compactness is my priority, spirals are chosen as candidate for further study. Inferences of this chapter are as follows:

- Metamaterials are artificially structured materials used to control and manipulate light, sound, and many other physical phenomena. The properties of metamaterials are derived both from the inherent properties of their constituent materials, as well as from the geometrical arrangement of those materials. Though there are many structures that qualify as metamaterials, the most common is that of an arrangement of elements whose size and spacing is much smaller relative to the scale of spatial variation of the exciting field. In this limit, the responses of the individual elements, as well as their interactions, can often be incorporated (or homogenized) into continuous, effective material parameters; the collection of discrete elements is thus replaced conceptually by a hypothetical continuous material. Metamaterials provide a path to multiscale design, in that the properties of the metamaterial elements can be first determined, with an equivalent, hypothetical continuous material used for subsequent system design.

- It is difficult to arrive at a strict and unambiguous definition of a metamaterial that wouldn’t exclude many types of structures that rightfully should be considered part of the metamaterials field.
For this reason, the definition above is purposefully somewhat vague. What is important, though, is that a metamaterial is not a tangible thing; rather, a metamaterial results from a design approach that satisfies the spirit of the above definition. The metamaterial concept has influenced the way we think about materials and device design, and in many cases has allowed us to identify solutions to problems in efficient and novel ways.

- Different metamaterial structures are studied and spiral is chosen as the suitable element for further application development. Spirals are compact, planar, easy to fabricate and inherent resemblance to nature adds to its beauty. Developed devices will not only be compact but aesthetically appealing too...

8.2 **Study of Spiral Inductors**

Spirals have undisputedly proved their inductive nature from the time world of magnetics was developed. This aspect is studied in depth in Chapter 2. Different characteristics like skin effect, proximity effect etc are studied. Limitations and methods to improve these characteristics are studied with the aim of utilising these for different applications. Spiral inductor has inbuilt capacitance along with its inductance, this can make the spiral to resonate. This is addressed in Chapter 3.

8.3 **Spiral Resonators**

In Chapter 3, three types of resonators (Type 1, Type 2 and Type 3) are studied for their CRLH nature. Parameter extraction is done for these resonators and it is found that extracted parameters match the performance
exhibited by all three resonators. A spiral resonator can work as both acceptor or rejection circuit. Throughout this thesis, the rejection capability is made use of and elaborated in next chapters.

### 8.4 Band Stop Filters

Implementation of different band stop filters through combinations of Type 1, Type 2 and Type 3 resonators is detailed in Chapter 4. This leads to simple wide band or dual band filters which are experimentally verified to get satisfactory performance. Parametric study is conducted and an empirical relation for designing Spiral Resonators are developed. Widely accepted optimisation technique Genetic Algorithm is used to predict the dimensions of Type 1 and Type 2 resonators for a desired frequency.

### 8.5 High Security Identity Cards

The curling nature of spiral towards the centre gives it a secretive nature. The secret data holding capacity is discussed in Chapter 5. Sharp resonance and fine tuning capability of Spiral resonators are used to develop unique identity cards. Frequency coding technique is used for ID card generation. Two resonators with or without proxy spiral are used to generate a 10 bit code from a card size of 1.5cm x 1cm. Compactness and high security outweigh the need for dedicated readers and fabrication accuracy.

### 8.6 Reconfigurable Antennas

In Chapter 6, Spiral resonators are embedded into open circuited transmission line to yield CRLH antenna (Type A and Type B). Reconfiguration capability of developed CRLH antenna is explored and it is verified whether the developed antenna possesses CRLH nature. It is seen
that the antenna exhibits Zeroth Order characteristics which is experimentally verified using first and second order antennas. Dispersion characteristics of antenna also show satisfactory results. First order antenna offers both frequency and radiation pattern reconfiguration; while second order exhibits only frequency reconfiguration. Type A and type B antennas fall under the category of ESA with compatible performance.

8.7 Sensor Antennas

Metamaterial structures are known to have intense near field. This property is made use of to develop sensor antennas. Five Spiral resonators proposed for sensor application are presented in Chapter 7. Comparison of these sensor antennas is done for soil and liquid sensing. Type B is tested for solid substrates with satisfactory results. Empirical relations are developed to assess the real part of substrate permittivity using Matlab™. A Graphical User Interface is also developed for the ease of estimation. A theoretical approach is put forward for assessing imaginary part of substrate permittivity. Moisture sensing capability is also tested on Type B antenna and found to give promising results.

8.8 Future scope

Spirals are an effective candidate for design of compact devices and it has been proved by studies presented in this thesis. Being compact, they can be integrated into practical circuitry with ICs. This aspect has to be tested and seriously looked upon. Absorbers and Electromagnetically Induced Transparency are areas not explored at length. Attention is to be diverted to these to open up large vistas of applications...
Metamaterials can find application in any field imaginable, be it communication, medicine, agriculture, building design and so on. I dream of a tomorrow when metamaterial becomes a familiar term to even common man and is indispensable to all. Let all the devices developed using metamaterial Spiral structure be beneficial to mankind, for the shape is known to us from time immemorial through nature in different forms...