DESIGN AND IMPLEMENTATION OF BROAD BAND AND NARROW BAND ANTENNAS AND THEIR APPLICATIONS

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The thesis deals with the design and implementation of broadband and narrowband antennas and their applications in practical environment. In this thesis, a new concept for designing the UWB antenna is proposed based on the CRLH metamaterials and this UWB antenna covers a frequency range from 2.45 GHz to 11.6 GHz. Based on the design of the UWB antenna, another antenna is developed that can cover a very wide bandwidth i.e from 0.66 GHz to 120 GHz. This antenna can not only be used for UWB applications but also for other communication systems working below the UWB spectrum such as GSM, GPS, PCS and Bluetooth. The proposed antenna covering the bandwidth from 0.66 GHz to 120 GHz is by far the largest bandwidth antenna developed based on metamaterials. Wide band antennas are not preferred for sensing purpose as it is difficult to differentiate the received signals. A multiband antenna which can be used as a strain sensor for structural health monitoring is proposed. The idea is to correlate the strain applied along the length or width with the multiple resonant frequencies. This gives the advantage of detecting the strain applied along any direction (either length or width), thus increasing the sensing accuracy. Design and application of a narrow-band antenna as a temperature sensor is also presented. This sensor can be used to detect very high temperature changes (>1000^0C). This sensor does not require a battery, can be probed wirelessly, simple and can be easily fabricated, can withstand harsh environmental conditions.

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I would like to express my sincere appreciation and gratefulness to my major advisor Dr. Hualiang Zhang for his knowledge, insight, guidance, constant mentoring and support throughout my entire research. Indeed, my gratitude to him cannot be expressed in few words and it was an honor to be his student. Appreciation is also extended to my friends and lab mates with whom I had some good conversations about all subjects in life and whose unconditional support and strength made every day enjoyable. I would like to thank my advisory committee members Dr. Xinrong Li, Dr. Gayatri Mehta and other faculty and staff members of the electrical engineering department for their moral support.

I am eternally indebted to my sister who has always been caring, loving and a constant source of inspiration. Lastly, and most importantly, I want to thank my parents. They bore me, raised me, supported me, taught me, and loved me. To them I dedicate this thesis.

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CHAPTER 1

INTRODUCTION

1.1 Motivation

IEEE defines antenna as a means for radiating or receiving waves. There are various types of antennas such as wire antennas, aperture antennas, microstrip antennas, array antennas, reflector and lens antennas. Wire antenna is the simplest of all antennas. It may take various forms such as rectangle, square, circle etc. Aperture antennas operate at higher frequencies and are useful for aircraft applications. The period during and after the World War II saw the advancement of the antenna from a simple wire to several other radiators such as slots, horns, reflectors, etc. The patch antenna was introduced in early 1970s and received a lot of attention since then. Microstrip antennas have been considered as excellent radiators due to their merits such as low profile and broadside radiation patterns [1]. Microstrip antennas are easy to fabricate and can be fed easily with a coaxial cable, microstrip line, etc apart from being easily integrable in an array. A single element has relatively wide radiation pattern and in order to achieve specific radiation patterns or high directivity, the electrical size of the single element can be increased. This technique seems good but is marred by mechanical problems. Another technique is to use multiple elements of the same size and form an array to achieve the required directivity. However, an efficient feeding network has to be designed to make the best efficient use of the array. Arrays form the best antenna systems. An array with identical elements is simple and easy to implement but this is not always necessary. In order to achieve high directive beam, it is necessary that the fields from all the elements of an array interfere constructively in the desired direction and destructively in other directions. The interference of the fields depends upon the spacing of the elements.

Future wireless communication systems particularly the Ultra wideband (UWB) systems require antennas with simple geometry, small size and uniform radiation characteristics. A conventional UWB antenna covers the frequency band from 3.1 GHz to 10.6 GHz. In the past, many designs had been proposed to work at this frequency band, where the goal was mostly concentrated on achieving the UWB bandwidth using different techniques without compromising the performance. Slot antennas, coupled slot antennas, planar monopole antennas, microstrip patch antennas with coaxial, microstrip, or coplanar waveguide feeds are a few examples. However, these antennas are limited to cover the conventional UWB bandwidth and any further development to improve the bandwidth is very difficult if not impossible. A new concept for designing UWB antennas covering wider bandwidth has to be developed so that it can be used for several applications such as GSM, GPS, PCS, and Bluetooth apart from UWB applications. In this thesis, we propose a new design for extremely wideband antenna based on the concept of log periodic antenna array technique.

Structural health monitoring (SHM) systems provide reliable information regarding the integrity of the structure such as building supports, bridges etc. SHM is the process to detect the damage or changes in the geometric properties of the structure before it exceeds the safety limit so that additional repairs and strengthening techniques can be applied, thus eliminating the risk of a possible collapse in the future. Various factors such as vibrations, cracks, ageing and natural disasters like earthquakes can contribute to the structural disturbances. In order to detect such kind of disturbances, SHM systems employ the strain measurement devices (e.g. strain sensor). Strain sensor is an important tool for monitoring and measuring the stress level in the structure as the load applied to it varies. Various strain sensors have been presented in the past but they are followed by drawbacks such as sensitivity to temperature, high cost, requires large space and battery. What we need is a simple strain sensor which can be monitored remotely, can be fabricated easily, low cost and does not require a battery.

A temperature sensor is a device which is used to predict accurate temperature of any given environment and convert it to a form which can be easily understood by any other device or observer. A good temperature sensor has to be very sensitive even for small changes in temperature. Several temperature sensors have been proposed such as Thermocouple based sensors, Resistance based temperature detectors (RTD's), thermistors and temperature –transducers IC's. Even RFID based wireless sensors have been proposed but they require a transceiver, a battery, a sensing element and an interfacing circuit to transform the data to simple electrical signals. However, even if we eliminate the cost of implementation of these sensors, they still cannot be used for detecting the changes in very high temperatures (>1000^{0}C). A simple temperature sensor that can be easily manufactured, can be easily implemented to detect very high temperatures is needed, thus eliminating the drawbacks of conventional temperature sensors.

1.2 Contribution of Thesis

In general, UWB system is not restricted to a single frequency band but can transmit over a broad range of frequencies. This characteristic differentiates it from other wireless technologies. The broad spectrum makes it resistant to interference, jamming and accurate ranging. By further increasing the bandwidth, the proposed UWB antenna can not only support the UWB spectrum, but also be used for many other electronic / communication systems including GSM, GPS, PCS, and Bluetooth. Moreover, the proposed antenna may find applications in radar systems, target sensing, locating, tracking and indoor geo-location applications. Among all of these applications, it is specifically useful for indoor geo-location systems to improve the sensing accuracy. Indoor geo-location refers to accurate determination of position of an object in an indoor environment where the probability to suffer from multi-path effect is very high. Due to this, the currently used positioning systems cannot provide accurate coverage for the indoor areas. This UWB antenna can be an ideal candidate for indoor geo-location because of its wide bandwidth which makes it resistant to interference and able to penetrate through concrete structures. The detailed analysis of UWB systems suggests that UWB antennas can be used in all the cases where we need a highly precise observation of objects at short distances. This antenna can also be used for short distance communications usually between computer components within a range of 10-15 meters.

Apart from UWB applications, there are various areas where the antennas can be of immense help such as structural health monitoring (SHM) and temperature sensor for sensing very high temperature changes .we have presented simple antenna designs in this thesis which can be used for the said applications.

1.3 Overview of Thesis

In this thesis, I intend to present new design for UWB, dual band and slot antennas and their applications.

Chapter 2 introduces a new design for extremely wideband antenna based on the concept of log periodic antenna array technique. Detailed analysis along with simulation and measured results are presented. Metamaterial based antennas are used as the radiating elements. These radiating elements are connected together and fed using parallel strip transmission lines. The proposed wideband antenna with its increased bandwidth can not only support the UWB spectrum, but also be used for many other electronic / communication systems including GSM, GPS, PCS, and Bluetooth.

Chapter 3 presents the concept the structural health monitoring (SHM) and temperature sensing using antennas. The concept on which the antennas have been designed is explained in detail in this chapter. A multi-band antenna is presented which can sense the strain along the length as well as width and also transmit the data, thus eliminating the drawbacks of the previous strain sensors. A simple slot antenna is also presented which can be used to detect the changes in temperatures >1000^{0}C. The antenna performance is simulated by the full-wave electromagnetic simulator (HFSS) and the simulation and measured results have been presented.

Finally, a conclusion is given in Chapter 4, where the future work for this thesis is also provided.

CHAPTER 2

LOG-PERIODIC ANTENNA ARRAY INSPIRED PARALLEL STRIP ULTRA-WIDEBAND (UWB) AND VERY WIDE-BAND ANTENNA

2.1 Motivation

Ultra-wideband (UWB) technology due to its high speed data rate communications, high accuracy radars, excellent immunity to multipath interference and large bandwidth has been attracting enormous interest worldwide. In general, UWB system is not restricted to a single frequency band but can transmit over a broad range of frequencies. This characteristic differentiates it from other wireless technologies. The broad spectrum makes it resistant to interference, jamming and accurate ranging. One of the key technologies in the UWB system that has been widely investigated by both academia and industries is the antenna design. Several antenna designs have been proposed since the release of the UWB spectrum by Federal communication commission (FCC) in 2002 to satisfy this spectrum requirement.

Recently, there has been a significant interest in developing low profile, light weight, and easy to manufacture wideband antennas. Meanwhile, different types of log periodic antennas due to its frequency independent characteristics have been proposed to work over a wide range of frequencies. The implementation of log-periodic principles in microstrip antennas is presented in [2-3], the characteristics of microstrip antenna is improved by log-periodic technique. In [4], an array of rectangular microstrip patches were arranged in log-periodic way and coupled to a microstrip feedline. [5] Presents a dual feed log periodic antenna with high gain and bandwidth. However, the size of these antennas is large due to the employment of multiple radiating elements.

In this chapter, I propose a new design for extremely wideband antenna based on the concept of log periodic antenna array technique. Metamaterial based antennas are used as the radiating elements. These radiating elements are connected together and fed using parallel strip transmission lines. The antenna performance is simulated by the full-wave electromagnetic simulator (high frequency structure simulator (HFSS)). The proposed wideband antenna with its increased bandwidth can not only support the UWB spectrum, but also be used for many other electronic / communication systems including GSM, GPS, PCS, and Bluetooth. Moreover, the proposed antenna may find applications in radar systems, target sensing, locating, tracking and indoor geo-location systems. Among all of these applications, it can be specifically useful for indoor geo-location (where the probability to suffer from multi-path effect is very high) to improve the sensing accuracy.

2.2 Antenna Design

The proposed antenna design is inspired by the concept of log-periodic antenna array technique, where an array of radiating element with narrow bandwidth is arranged in a log-periodic way to increase the bandwidth [2 - 5]. Based on this technique, in this paper, two independent metamaterial based wideband antenna elements have been designed covering different radiating frequencies and are combined together to give more bandwidth. The basic design of the antenna element used in the proposed UWB antenna is based on the concept of composite right/left-handed (CRLH) metamaterial antenna [6]. Fig. 2.1 shows the structure of the antenna element used in the proposed antenna. This antenna element consists of a circular patch of radius R = 3.5mm, a semi-circular portion with wings and a straight section to which the power is delivered through a parallel-strip line (this feeding line will be discussed later). The length of the wings (L as labeled in Fig. 2.1) is 1.68mm each. The semicircular portion feeds the circular patch through capacitive coupling. The gap between the circular patch and the semicircular patch has to be designed carefully so that there is enough generation of capacitance which is essential to get a better matching throughout the entire bandwidth. If this coupling is too tight, the radiation performance will be adversely affected. The bottom portion of the parallel stripline behaves as a ground plane, and the width of it is chosen to be 8mm. The width of the ground plane is pivotal for providing a better performance of the antenna element. A metallic via connects the circular patch on the top layer to a via line at the bottom layer which leads to the ground plane, providing parallel inductance. The radius of the via is 0.3mm and the width of the via line is 0.2mm. The combination of the inductance (induced by the via line) and the capacitance (induced by the coupling gap) forms the CRLH type metamaterial, leading to a compact antenna design.

For the feeding of the proposed antenna, previously, most of the antennas were fed by coaxial line [6], microstrip line [7]-[8], or CPW line [9]-[10], but in this chapter we propose to use the parallel-strip lines. As shown in Fig. 2.2, a parallel-strip line is made of a symmetrical pair of strip conductors on opposite faces of a dielectric material which makes it compatible with double sided antennas and other balanced microwave circuits [11 - 16]. Most importantly, this kind of transmission line can provide the following attractive features: (1) it provides wide operating bandwidth; (2)

it is easy for the implementation of the log-periodic array concept; (3) it improves the power handling capability along with reducing the complexity of circuit structures of wide band transitions; and (4) it is easy for the realization of low characteristic impedance line and good performance of balanced microwave components. All of these properties have made it appealing to apply parallel-strip line in the proposed UWB antenna. In this design, the width (W1 as labeled in Fig. 2.1) of the parallel stripline is calculated to be matched to a characteristic impedance of 50 ohm (W1 as labeled in Fig. 2.1) and is 2.2mm and the length (L1 as labeled in Fig. 2.1) was determined to be 20.7mm.

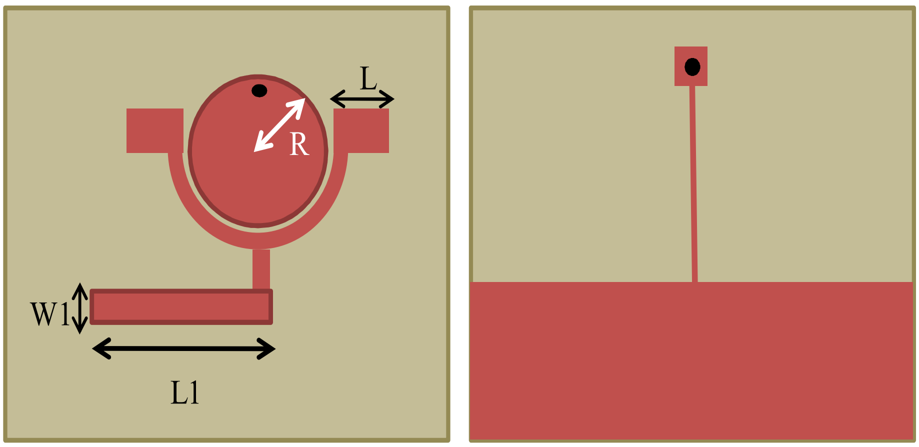


Fig. 2.1. Topology of the antenna element used in the proposed UWB antenna: (a) top view, (b) bottom view.

The final schematic of the proposed antenna is shown in Fig. 2.3, where two antenna radiating elements (metamaterial based antenna) are connected with the help of the parallel-strip lines. The first antenna element resonates well in the high frequency band covering the frequencies from 5.2 GHz to 9.4 GHz. The second antenna element is designed by scaling the first antenna element by a factor of 2.

However, in the second element the width and length of the parallel stripline is kept same as the one used in first element. The second element covers the lower band with the operating frequency ranging from 2.7 GHz to 5.2 GHz. The two antenna elements have overlapping operating frequency band, which is essential to obtain a stable performance in the resultant antenna bandwidth. The ground plane is adjusted in a way such that both the antennas operate properly. The overall size of the proposed antenna is 40 mm by 40 mm.

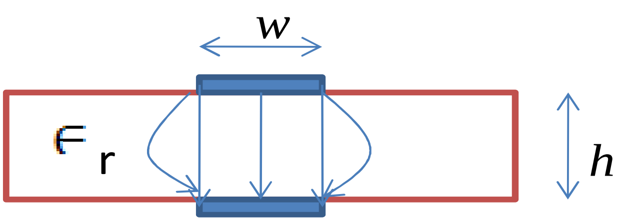
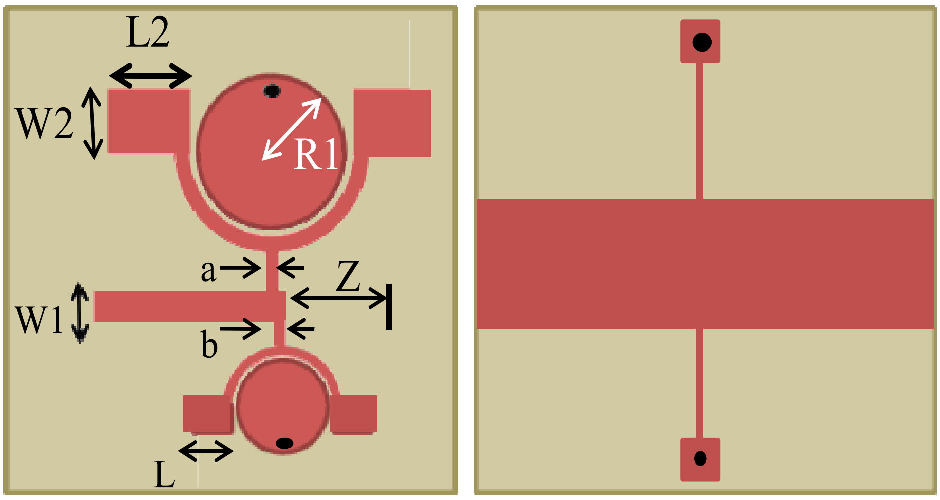


Fig. 2.2. Cross section of a parallel strip transmission line.



(a) (b)

Fig. 2.3 Schematic of the proposed UWB antenna: (a) top view, (b) bottom view.

2.3 Results and Discussion

The numerical analysis of the proposed antenna is performed using the full-wave simulation software HFSS. Through our simulations, an FR4 board is used with thickness = 1mm, relative permittivity ϵ_r=4.4 and loss tangent=0.02. Fig. 2.4 shows the simulated VSWR for the two individual antenna elements, covering the higher and lower frequency bands. The first antenna element covering the higher frequency band has a fractional bandwidth of 57.5% corresponding to a center frequency of 7.3 GHz and the antenna element covering the lower frequency band has a fractional bandwidth of 67.5% at a center frequency of 4 GHz. The whole performance of the proposed antenna is also plotted in Fig. 4. It has a fractional bandwidth of 138% at center frequency of 7 GHz; covering the frequency band from 2.45 GHz to 11.6 GHz (the whole UWB band from 3.1 – 10.6 GHz is covered). As labeled in Fig. 2.3, the physical dimensions of the designed antenna are: W1=2.2mm, W2=15mm, L=1.68mm, L2=11mm, R1=7.4mm, a=0.2mm, b=1.4mm and Z=0mm. During our simulations, it was found that several parameters will affect the antenna's performance. To study the effect of these parameters, parametric studies are conducted. First, the effect of the width of the straight section of larger antenna element ('a' as labeled in Fig. 2.3) is studied. Fig. 2.5 shows the simulated VSWRs with the values of 'a' changing from 0.2mm to 1mm in a sweeping step of 0.2mm. It is observed from this figure that the performance of the antenna in lower frequency band will be affected greatly by this parameter. As a compromise of the antenna performance and the fabrication resolution, $a = 0.2$ mm is used in the final design.

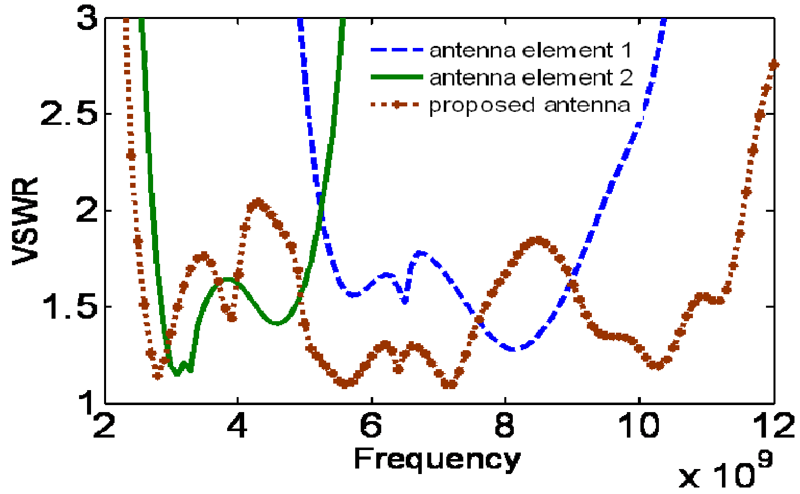


Fig. 2.4 Simulated VSWR of the antenna element covering the higher frequency band (antenna element 1) and the lower frequency band (antenna element 2) and the proposed antenna.

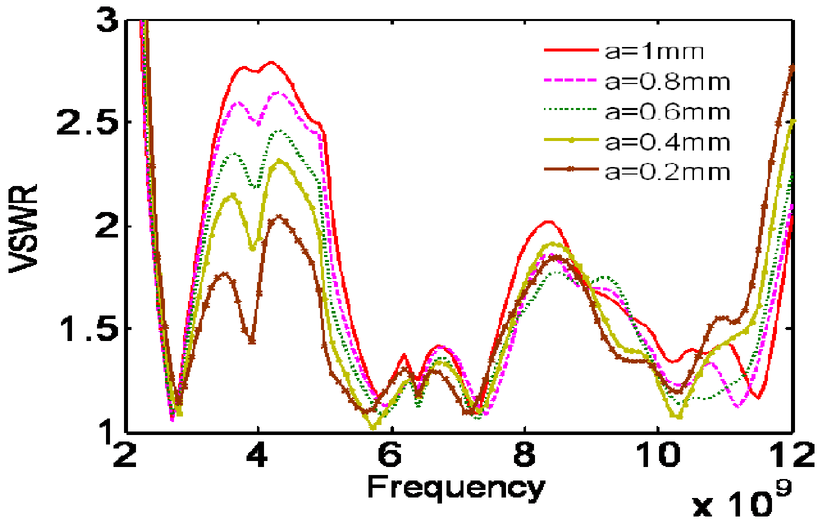


Fig. 2.5. Simulated VSWR of the proposed antenna covering the band from 2.45GHz to 11.6GHz, for different values of *a*.

Next, the effect of the parallel stripline length to the antenna's performance was studied. Fig. 2.6 presents the simulated results for different values of *Z* (as labeled in Fig. 2.3). In our simulations, initially, the length of the parallel strip was assumed to be 21.2mm (*Z* = 0.5mm). This parameter was then swept with a step size of 0.5mm. It is found that the optimal antenna performance is achieved when *Z* = 0mm. In this case, the two straight sections of the antenna elements are exactly aligned at the end of the strip. Fig. 2.7 shows the fabricated antenna structure and the corresponding measured VSWR is presented in Fig. 2.8. The simulated and measured results are in good agreement with each other. Finally, the radiation characteristics of the proposed antenna at discrete frequencies over the whole operating frequency band are plotted in Fig. 2.9. The proposed UWB antenna exhibits omni-directional radiation patterns at lower frequencies. At the higher operating frequencies, the original omni-directional radiation patterns are distorted.

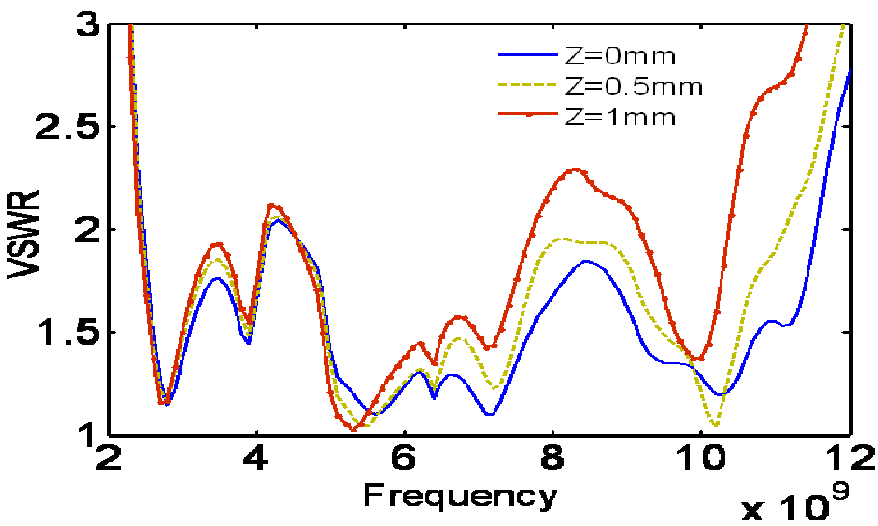


Fig. 2.6. Simulated VSWR for different values of *Z*.

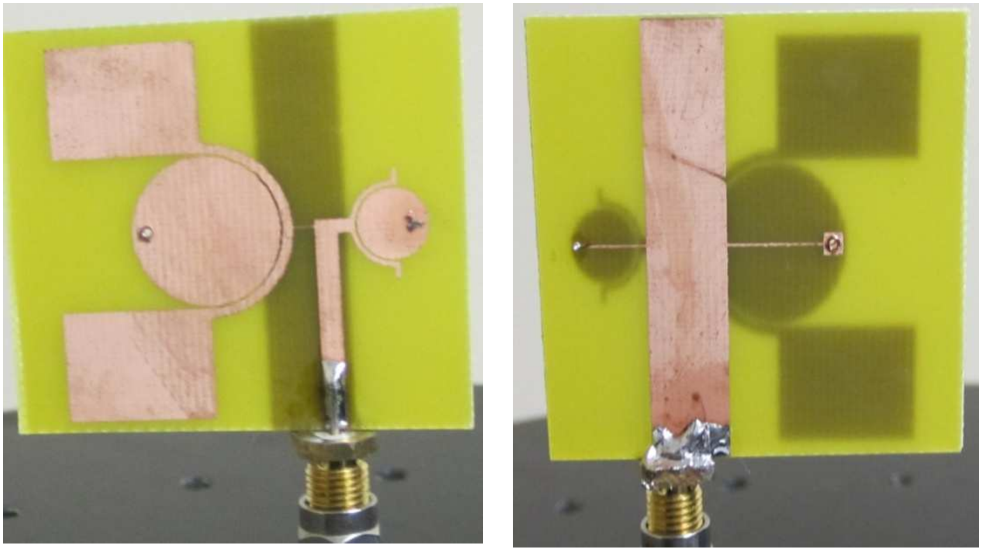


Fig. 2.7. Fabricated antenna structure: (a) top portion, (b) bottom portion.

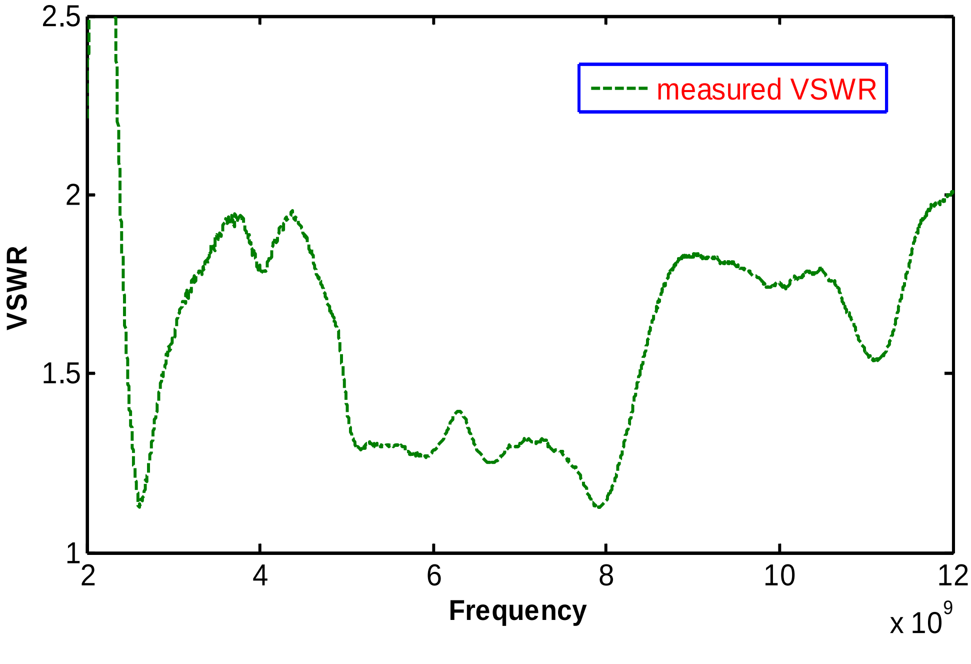
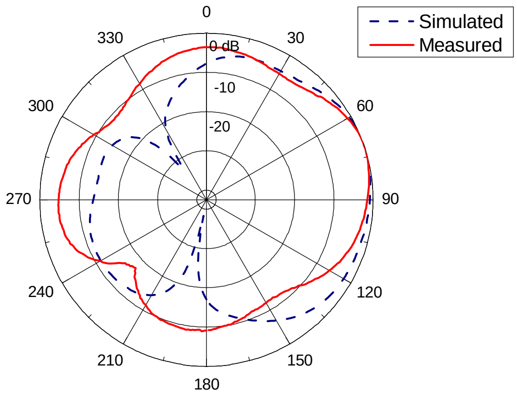
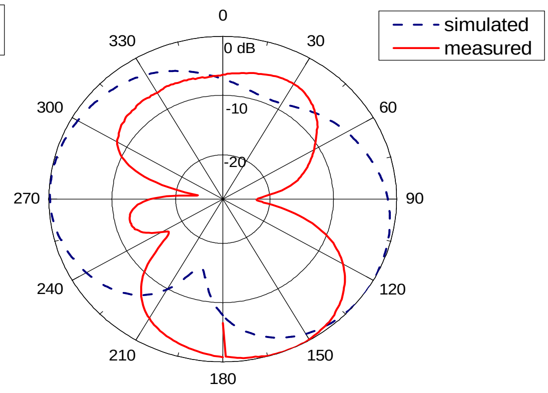


Fig. 2.8. Measured VSWR of the proposed antenna



(a)



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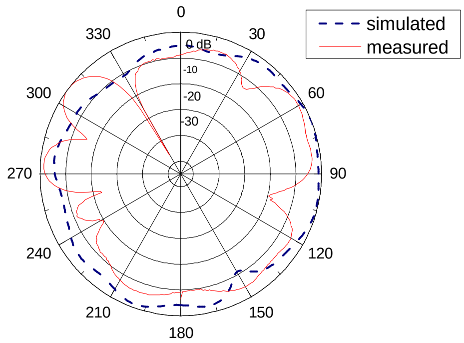

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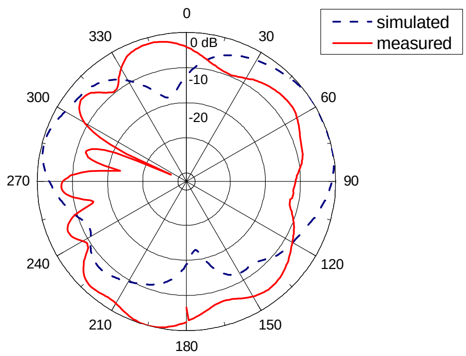
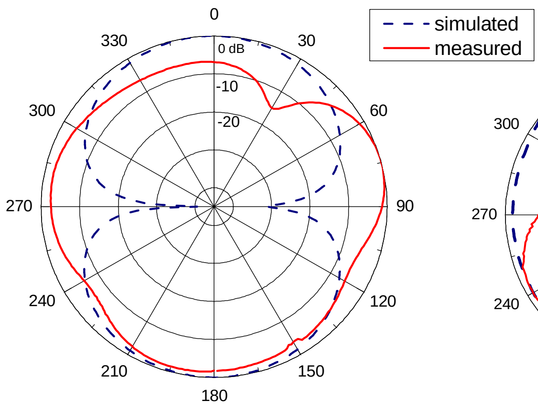
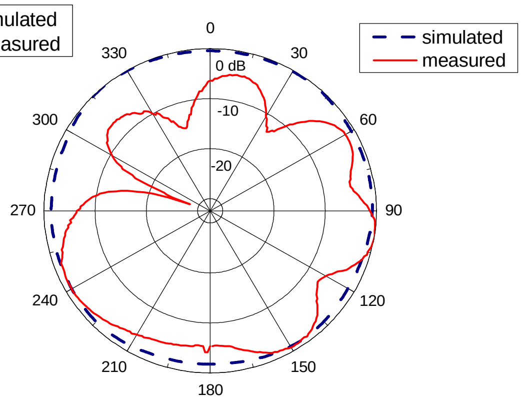


(b)

Fig. 2.9(a). Simulated and measured antenna's radiation patterns at different frequencies corresponding to E-plane co and cross polarization (a) 3 GHz (b) 7 GHz



(a)



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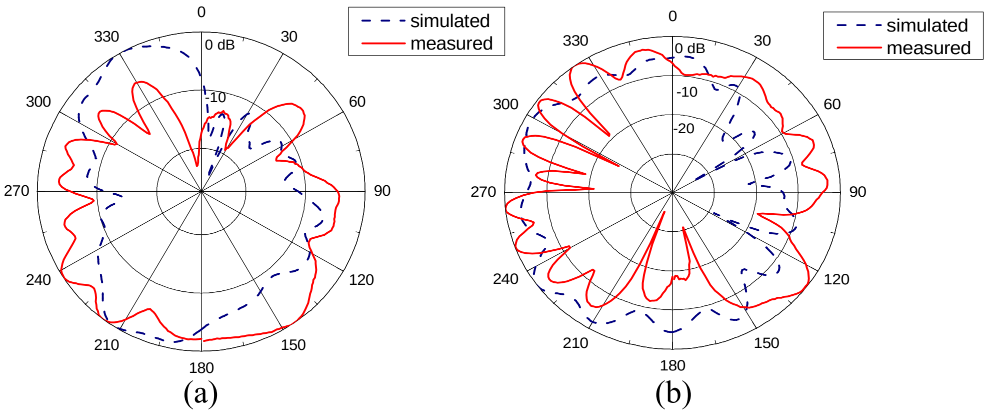
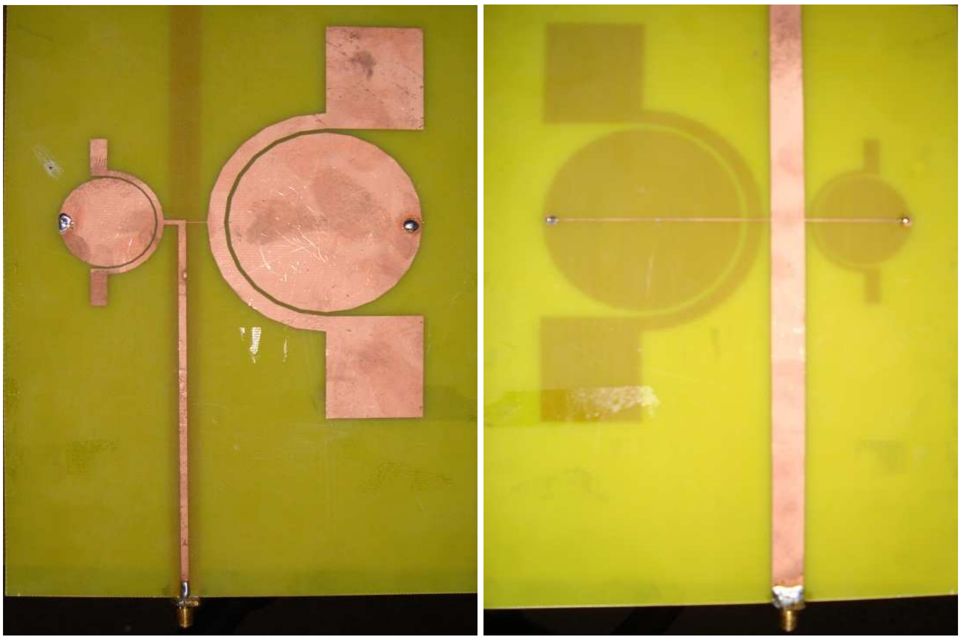


Fig. 2.9 (b) Simulated and measured antenna's radiation patterns at different frequencies corresponding to H-plane co and cross polarization (a) 3 GHz (b) 7 GHz

In order to increase the bandwidth further and cover the much lower frequency band, the antenna shown in Fig. 2.1 was then scaled by 4 times its original value. After performing the optimization of several parameters of the scaled antenna, resulted in an antenna resonating from 0.6GHz to 120GHz with a VSWR <2 for the frequencies from 3.5GHz to 120 GHz and a VSWR<3 for frequencies from 0.6GHz to 3.5GHz. But the parallel strip was still maintained to give an impedance of 50 ohm at lower frequency band and was modified accordingly. Fig. 2.10 shows the fabricated very wide band antenna. Fig. 2.11 shows the simulated and measured return loss of the scaled antenna from 0.6GHz to 120GHz and they are in good agreement with each other. Fig. 2.12 shows the simulated and measured results for the frequencies from 0.6GHz to3GHz.



(a) (b)

Fig. 2.10 Fabricated very wide band antenna: (a) top side, (b) bottom side

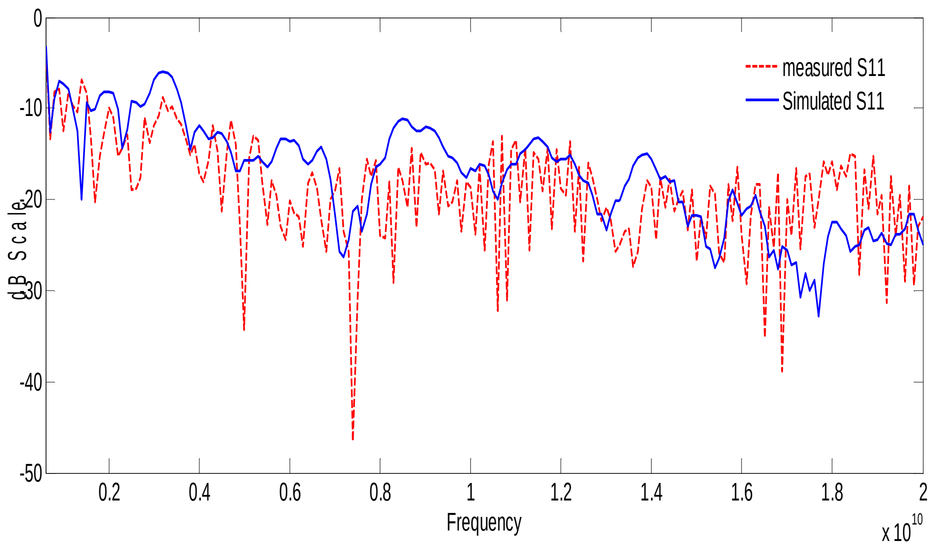


Fig. 2.11. Simulated and measured results of the scaled antenna

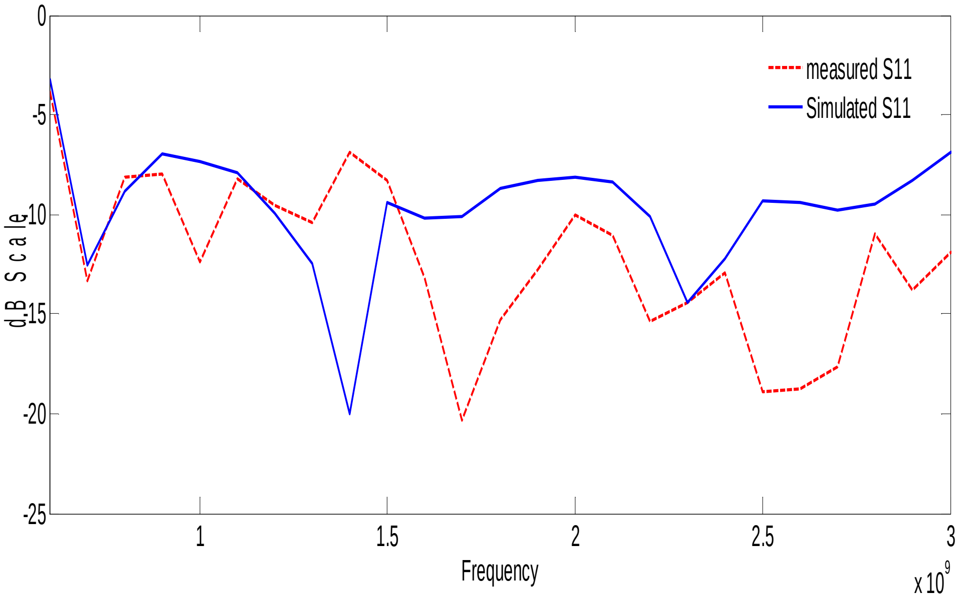


Fig. 2.12. Simulated and measured results of the Scaled antenna for lower frequencies

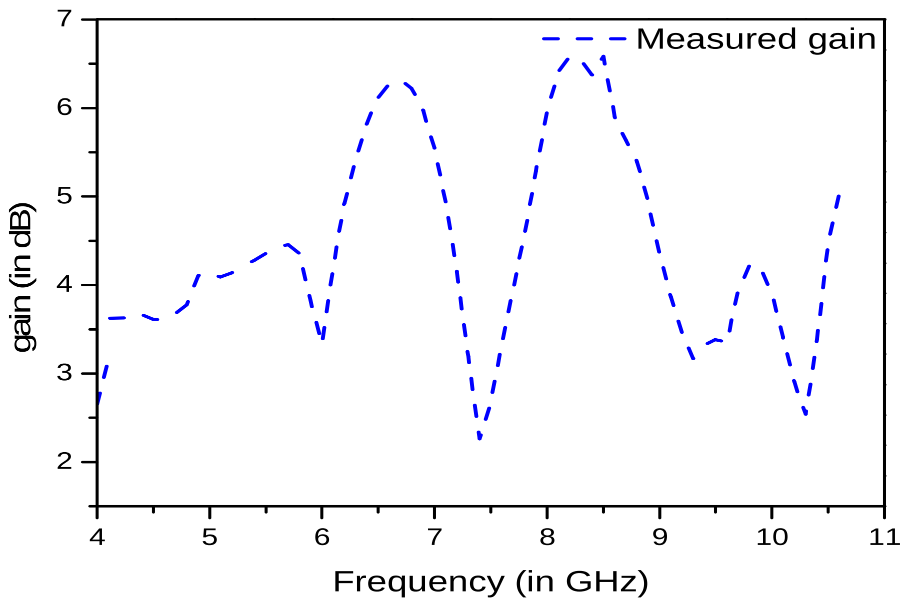
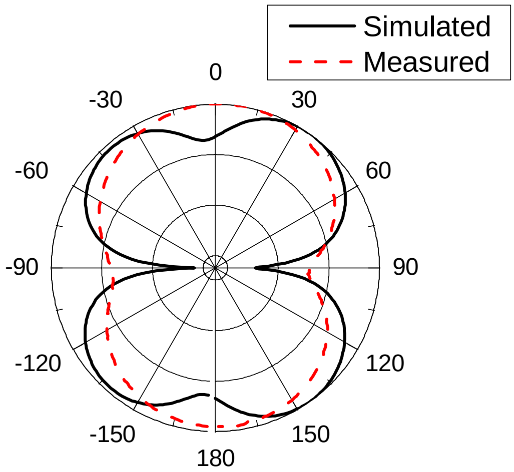
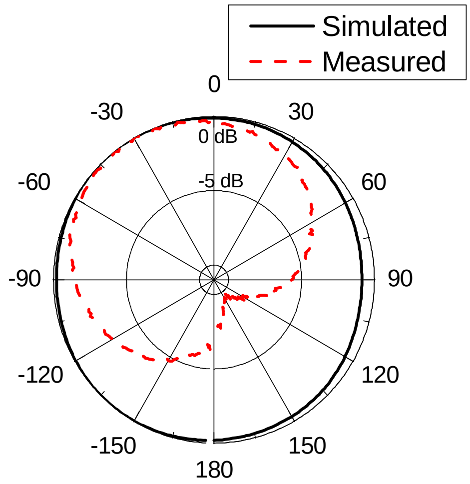


Fig. 2.13 Measured gain of the proposed wide band antenna



(a)



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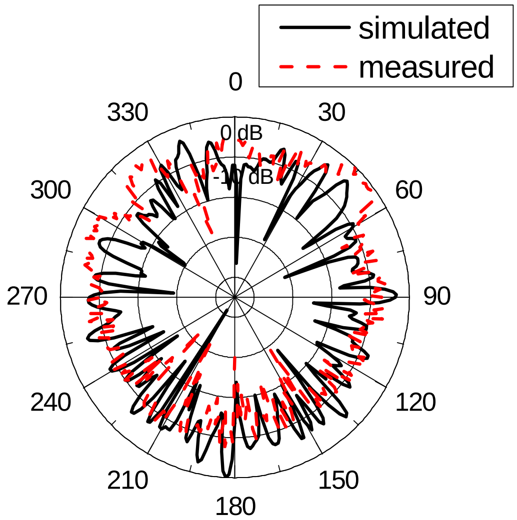
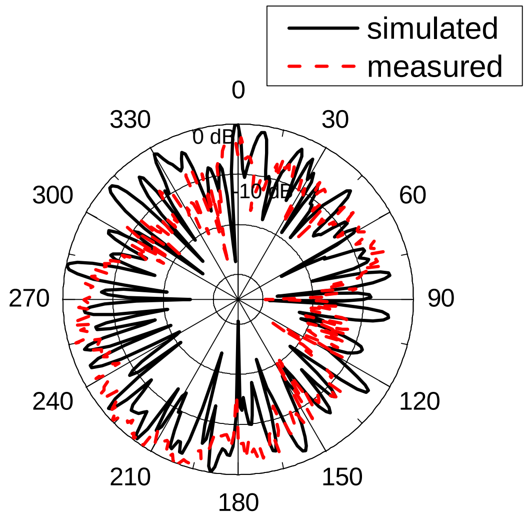
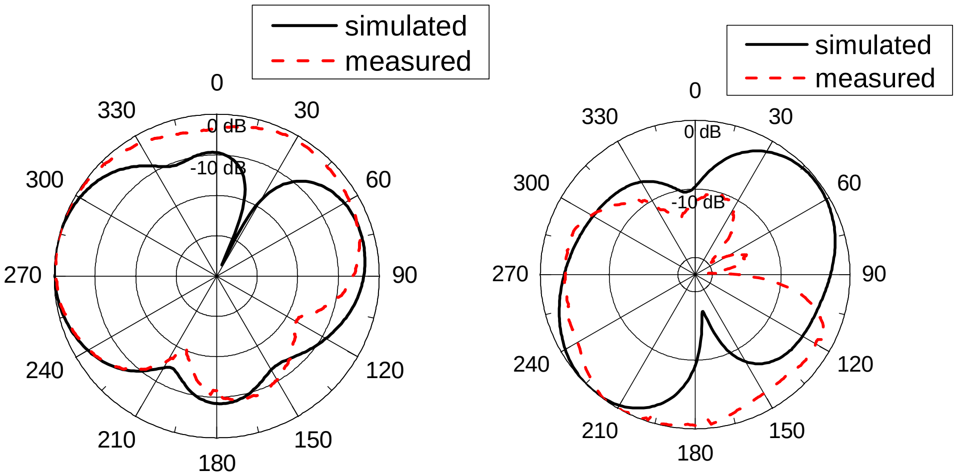


(a)

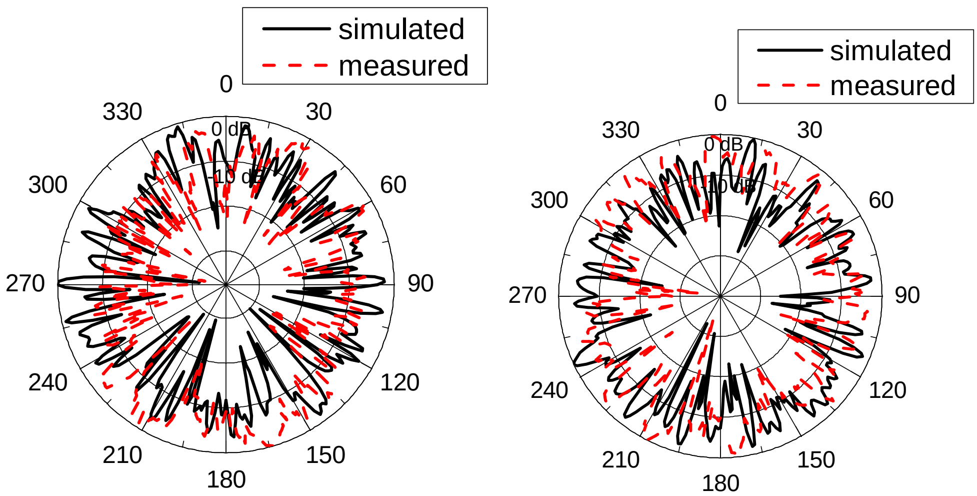


(b)

Fig. 2.14 (a). Simulated and measured radiation pattern for E-plane: (a) co polarization, (b) cross polarization at 1GHz and 13GHz



(a) (b)



(a) (b)

Fig. 2.14 (b) Simulated and measured radiation pattern for H-plane: (a) co polarization, (b) cross polarization at 1GHz and 13GHz

Gain of an antenna is defined as the ratio of the intensity in a given direction to the radiation intensity radiated isotropically. Fig. 2.14 shows the measured gain of the antenna over a frequency range from 4GHz to 10.6GHz. The max gain of 6.6dB is obtained at 8.3GHz. Radiation patterns of the scaled antenna are shown in Fig. 2.14 (a) and (b), both co and cross polarization in E and H plane. The patterns are omni directional at lower frequencies and distorted at higher frequencies due to higher order modes.

2.4 Summary

A new design concept of UWB antenna is presented, proving that two individual wideband antennas can be connected together in a way inspired by the log periodic antenna array technique using a parallel stripline. The UWB antenna covers the frequency band from 2.45 GHz to 11.6 GHz, defined with a VSWR < 2, thus encompassing the bandwidth of the two individual antenna elements. The simulated radiation patterns at different frequencies with the corresponding E-plane and H-plane are also presented. Numerical results and measured results show that the proposed antenna is suitable for various broadband applications. Further, to cover much lower frequencies, the UWB antenna was scaled by a factor 4 and after several modifications and optimizations of several conflicting parameters an extremely wideband antenna was obtained which covers the bandwidth from 0.68GHz to 120 GHz, defined with a VSWR < 3 for frequency range of 0.68GHz to 3.3GHz and VSWR<2 for 3.5GHz to 120GHz.

CHAPTER 3

APPLICATION OF ANTENNA IN STRAIN AND TEMPERATURE MEASUREMENT

3.1 Motivation for Strain Measurement Antenna

Structural health monitoring (SHM) systems provide reliable information regarding the integrity of the structure such as building supports, bridges etc. SHM is the process to detect the damage or changes in the geometric properties of the structure before it exceeds the safety limit so that additional repairs and strengthening techniques can be applied, thus eliminating the risk of a possible collapse in the future. Various factors such as vibrations, cracks, ageing and natural disasters like earthquakes can contribute to the structural disturbances. In order to detect such kind of disturbances, SHM systems employ the strain measurement devices (e.g. strain sensor). Strain sensor is an important tool for monitoring and measuring the stress level in the structure as the load applied to it varies. A variety of strain sensors have been used in the past. Semiconductor strain gauge called the piezoresistor, based on the piezoresistive effect is the commonly used strain gauge. Several piezoresisitive strain sensors have been designed to be used for various strain measurements with an excellent gauge factor [17-19]. However they are very sensitive to temperature changes. In [20], it is proved that by increasing the doping level, piezoresistive sensors which are less sensitive to temperature variation can be obtained but with reduced gauge factor. They are also very delicate and hence it is difficult to implement them in a commercial environment considering the complexity of the network involved.

Recently, there has been a significant research on the optical fiber based strain sensors. A detailed overview of applications of optical fibers in mechanical measurements can be found in [21]. An optical fiber sensor with a linear relation between transmitted light intensity and applied stress is presented in [22]. A twisted pair of optical fiber has been used in [23] to determine the stress in an optical cable due to thermal expansion. Optical fibers have the advantage of high bandwidth and free from electromagnetic interference but high cost of implementation has made it prohibitive for usage along with robustness of the sensor system, transduction, data interpretation, stability and reliability [24].

Easy and low cost availability of RF transceivers and microcontrollers resulted in the integration of wireless technology and sensing devices. A number of wireless strain sensors have been presented in [25-27]. These wireless sensors require batteries to charge along with a complex data transmitting system. For convenient maintenance of the structures of interest, SHM systems should be provided with wireless and battery less and simple passive strain sensors.

In this chapter, a multi-band antenna is presented which can sense the strain along the length as well as width and also transmit the data, thus eliminating the drawbacks of the previous strain sensors. The antenna performance is simulated by the full-wave electromagnetic simulator. This chapter is organized as follows. The design of antenna and simulated results are first discussed, followed by a discussion on mechanical arrangement for the testing of the antenna, and finally the measured results which support the use of antenna as a strain measurement device.

3.2 Antenna Design and Simulated Results

Fig. 3.1 shows the general structure of the antenna. The proposed antenna has a patch on one side and ground plane on the other side (a microstrip structure) with a dielectric substrate at the center. This forms an electromagnetic cavity. Due to the effect of additional slots designed on the antenna, this antenna resonates at multiple frequencies. There are 13 slots on the patch and the dimension of each slot is 5mm by 0.3mm. The total dimension of the antenna is 19.8mm by 17.9mm. The width of the feed-line with 50 ohm impedance is calculated to be 0.76mm. This antenna was designed and fabricated on Rogers' RT/ duroid 5880 substrate with a substrate thickness of 0.254mm, dielectric constant of 2.2, and a loss tangent of 0.0009. The fabrication cost for the antenna is very low compared to the previous strain sensors. For a simple patch antenna, when a positive strain is applied along the length, the resonant frequency shifts to a lower value due to the elongation along the length and when the same strain is applied along the width direction, the resonant frequency shifts to a higher value due to Poisson's effect [28]. The relation of the effective dielectric constant ϵ_{re} with the dielectric constant ϵ_r, thickness of the substrate (h) and the width of the electrical patch (W) can be expressed by the equation

$$\varepsilon_{re} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2\sqrt{1 + 10h/W}} \qquad (1)$$

From (1), it can be deduced that, with the change in the height of the substrate and the width of the patch antenna, the effective dielectric constant changes, which results in the variation of the resonant frequency. The proposed antenna is expected to behave in a similar manner (since the whole antenna can be thought as a patch). The main purpose of the slots is to improve the sensitivity of the antenna and this happens when the coupling between the slots changes with the increasing strain along the length / width. Fig. 3.2 shows the simulation results for the proposed antenna along the width and length direction. The simulation of the antenna was performed using full-wave electromagnetic simulator (High Frequency Structure Simulator (HFSS)) with an assumption that for different strains applied along the length and width, the height of the substrate will remain constant, the metal patch will experience elongation along length and patch width will behave according to Poisson's effect. The Poisson's effect to the substrate is not considered in our simulation for the easiness of numerical simulation (Note: the dominant factor in affecting the resonant frequency is the antenna's dimension change). The first resonant frequency as shown in Fig. 3.2(a) corresponds to the width and increases with the increase in strain along width direction and the remaining two resonant frequencies shown in Fig 3.2(b) corresponds to the length, which decreases with increasing strain along length direction. We believe the simulation results can serve as a reference for the measurement results.

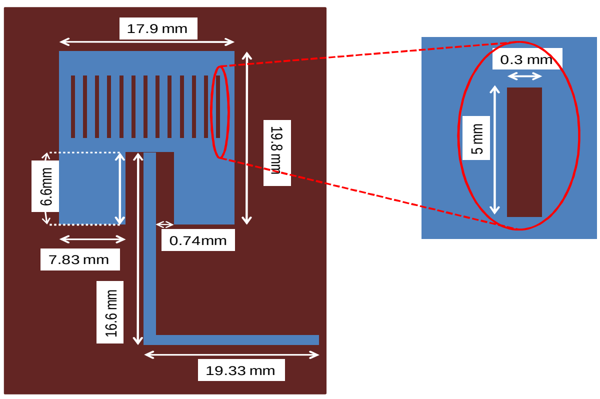
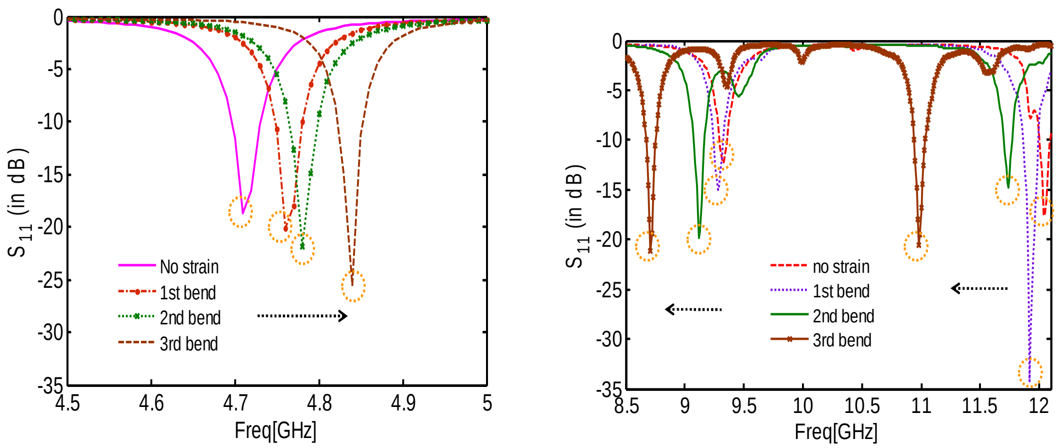
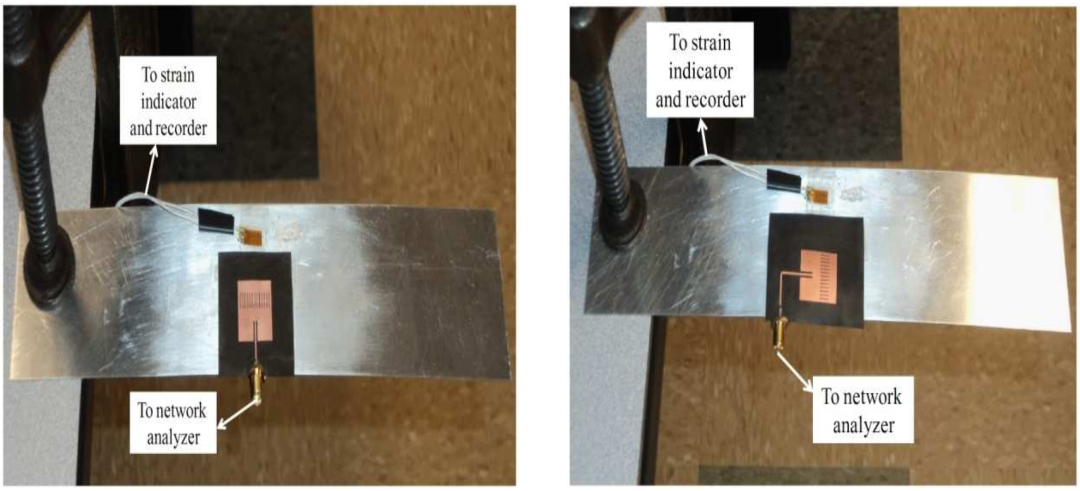


Fig. 3.1 Topology of the proposed antenna.



(a) (b)

Fig. 3.2 Simulated antenna performance with different bendings, (a) along width (b) along length.



(a) (b)

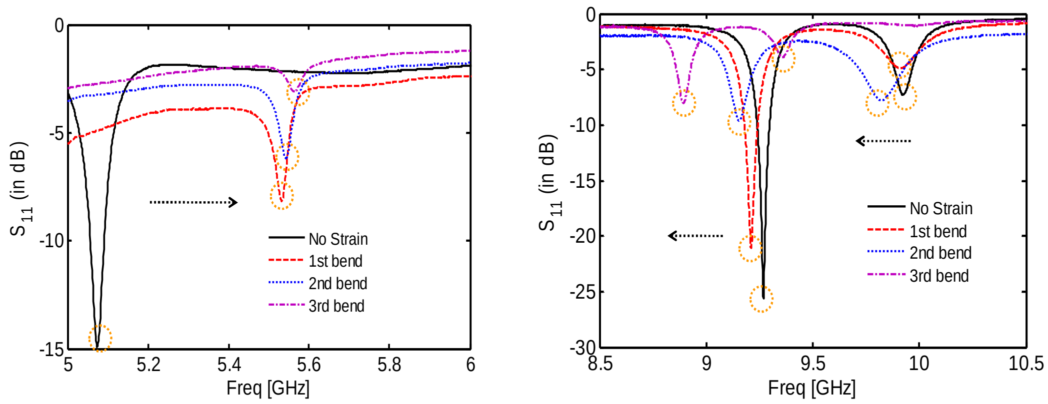
Fig. 3.3 Test arrangement for bending along different directions, (a) along width direction (b) along length direction.

3.3 Testing of the Antenna

Fig. 3.3 shows the mechanical arrangement for the testing of the antenna along the width and length directions. A cantilever beam of considerable thickness is used in order to provide more sensitivity when a small load is applied. M-bond 200 adhesive was used to attach the antenna and the metal foil strain gauge to the metal beam. Strain gauge is connected to a strain indicator and recorder which give an approximate value of strain experienced for each increment of the load. Antenna is fed by the vector network analyzer through an SMA connector. The measured antenna performance (S_{11}) is collected in this way. Care should be taken to make sure that a good solder is provided for the connection between the SMA connector and the feeding stripline so that the electrical connection between them remains stable even when the structure experiences different bends. As it can be observed from Fig. 3.3, the two antennas have different feed-lines (non-folded and folded), which makes the measurement easier for different directions.

3.4 Measured Results

The measured results are presented in Fig. 3.4 for different strain applied along the width and length directions. From the measured results as shown in Fig. 3.4(a), it can be concluded that the first resonant frequency which occurs at 5.07 GHz (without any bend) corresponds to the width and will move to a higher value as the value of the strain along width increases. The three successive bends caused by the increasing strain shift the resonant frequency from 5.07 GHz to 5.53GHz, 5.54 GHz and 5.56 GHz respectively. The remaining two resonant frequencies which occur at 9.27 GHz and 9.93 GHz (without any bend), shown in the Fig. 3.4(b) corresponds to the length and moves to a lower value when the strain applied along the length is increased. Table 3.1 gives the value of the strain obtained for each bending state with different load and Table 3.2 gives the frequency changes obtained for different bends along the width and length directions. As compared with Fig. 3.2, even though the simulation was performed with ideal conditions, the measured results show the similar characteristics, thus proving our design concept.



(a) **(b)**

Fig. 3.4 Measured results (a) along width (b) along length.

Table. 3.1 Antenna under test (AUT) with different bending and corresponding strains

State of Bending	Strain Applied (unit: microstrain)
no bending	0 με
bending state 1	3316 με
bending state 2	4480 με
bending state 3	6965 με

Table. 3.2 Antenna under test (AUT) with different bending and corresponding frequency change

State of Bending	Freq.(along width)	Freq.(along length)	
no bending	5.07 GHz	9.26 GHz	9.93 GHz
bending state 1	5.53 GHz	9.21 GHz	9.91 GHz
bending state 2	5.54 GHz	9.15 GHz	9.82 GHz
bending state 3	5.56 GHz	8.89 GHz	9.36 GHz

3.5 Motivation for Temperature Sensing Antenna

A temperature sensor is a device used to predict accurate temperature for any source and converts it to a form easily understood by any observer or another device. Temperature sensors come in many different forms and are used for a wide variety of purposes such as detecting the temperature change from simple home to the change of temperature at extremely dangerous furnaces where the interference of humans is impossible.

Several sensors have been used in the past. Thermocouples form the simple sensor with complex function [29-30]. A thermocouple consists of two dissimilar metals, joined together at one end, and produces a small unique voltage at a given temperature. The thermocouples work on the principle of Thermocouple effect, where one junction of the thermocouple is the sensing element and the other junction is set at reference temperature. However, the measurement is complex with potential sources of error.

Resistivity of metals is highly influenced by the temperature and this led to resistance temperature detectors (RTDs). But, they suffer from low sensitivity, higher cost than thermo couples and affected by shock and vibration.

A significant amount of research has been contributed to the development semiconductor temperature sensors. These sensors are small, accurate and inexpensive but the use is limited to applications where temperature range is only a few hundred degrees (generally <150 degrees). However, capacitively loaded MEMS sensors have been developed which can sense up to a temperature of 300^0C [31].

In this chapter, a simple slot antenna is presented which can sense the temperature greater than 1000^0C, thus eliminating the drawbacks of the previous sensors. Since the antenna has no additional elements, it doesn't need calibration, never wear out and can work under any environmental conditions apart from being inexpensive and easy to use. The antenna performance is simulated by the full-wave electromagnetic simulator.

3.6 Antenna Principle, Design and Simulated Results

This antenna works on the following principle. As the temperature increases, the dielectric constant of the substrate decreases and this shifts the resonant frequency of the antenna to a higher value. In this configuration, when an incident wave hits the surface of the antenna, then the reflected wave will be shifted in frequency according to the change in the temperature, thus giving us the advantage of remotely probing the antenna from a distance. Fig. 3.5 shows the general structure of the antenna. The proposed antenna has a ground plane with a slot and this is fed by a magnetically coupled transmission line of 50 ohm impedance. The width of the transmission line is calculated to be 0.1mm. The total dimension of the antenna is 16mm by 18mm and the dimensions of the slot are 2mm by 12mm. This antenna was designed on Zinc oxide substrate with a thickness of 0.1mm, dielectric constant of 11 and loss tangent of 0.02. Fig. 3.6 shows the simulated results of the antenna for different dielectric constants which can be attributed to different values of temperature (increasing values).

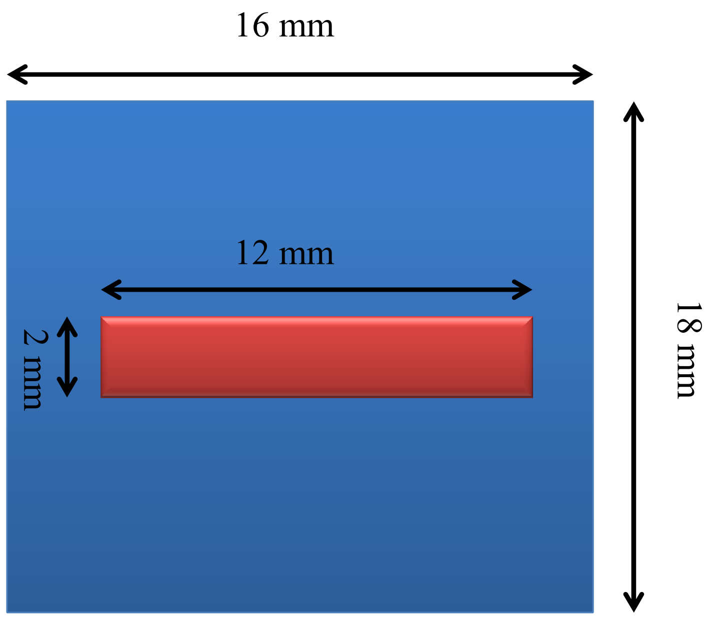


Fig. 3.5 Topology of the proposed temperature sensor antenna

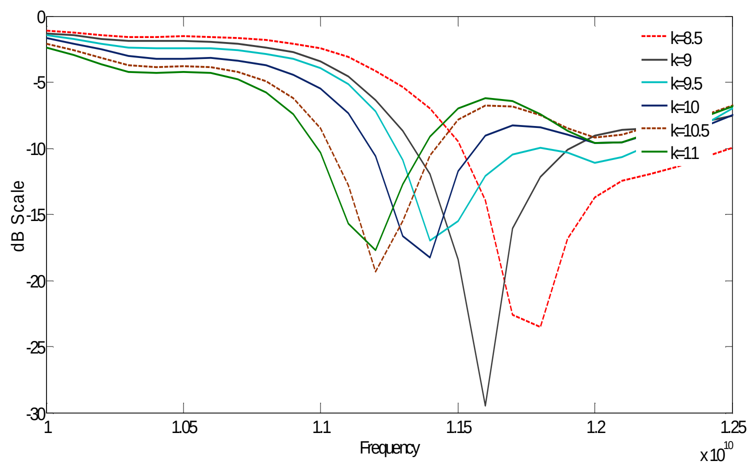


Fig. 3.6 Simulated results of the proposed temperature sensor

From the simulated results, it can be concluded that as the temperature increases, the dielectric constant decreases and the resonant frequency increases, thus proving the design concept.

3.7 Summary

In this chapter, analysis of a slotted patch antenna as a strain measurement device and its response for different strains along the length and width has been studied. The proposed patch antenna is more sensitive to strain along the length when compared with the strain applied along the width. The simulated and the measured results have been presented, verifying our design concept. In the future, this cable can be replaced by a receiving antenna (using the antenna's back-scattering effect), resulting in a low-cost wireless strain measurement device. Also, a more detailed analysis is required to further study the relation between shifting of the frequencies and load applied in order to improve the strain measurement accuracy.

Also, a new slot antenna which can be used as a remote temperature sensor for very high temperatures (usually >1000^{0}C) is presented. The proposed antenna has a linear frequency change from 11.2GHz to 11.8 GHz. Using the antenna's back scattering effect, this antenna can be remotely monitored.

CHAPTER 4

CONCLUSION

In this thesis, a detailed discussion of the design of broadband and narrow band antennas and their applications is presented.

I have presented a new concept for designing a Ultra wideband antenna which can cover a wide bandwidth, proving that two individual wideband antennas can be connected together in a way inspired by the log periodic antenna array technique using a parallel stripline. The UWB antenna covers a wide frequency band encompassing the bandwidth of the two individual antenna elements. In order to cover more bandwidth, this UWB antenna was scaled by a factor of 4 and after a lot of effort involved in optimization of several parameters that were found to have an adverse effect on the antenna's performance; a stable bandwidth of 0.66GHz to 120GHz was obtained. This is by far, the largest bandwidth achieved for antenna based on CRLH metamaterial concept.

Several strain sensors are available in the market for structural health monitoring (SHM). In chapter 3, I have addressed the issues related to the current strain sensors came up with a new antenna design concept which can overcome the drawbacks of the previous sensors. Analysis of a slotted patch antenna as a strain measurement device and its response for different strains along the length and width has been studied. During the simulations and testing of the antenna, it was observed that the proposed patch antenna is more sensitive to strain along the length when compared with the strain applied along the width. The simulated and the measured results have been presented, verifying our design concept. For testing the current antenna we have used a cable to probe it but in the future, this cable can be replaced by a receiving antenna (using the antenna's back-scattering effect), resulting in a low-cost wireless strain measurement device. The relation between shifting of the frequencies and load applied is to be studied in more detail to further improve the strain measurement accuracy.

We have also presented a simple slot antenna and its application as a temperature sensor. This antenna can sense very high temperature changes (usually >1000^{0}C), which make it suitable for working under extreme conditions. This antenna too can be probed wirelessly using the antenna's backscattering effect which makes it a brilliant passive temperature sensor.

APPENDIX

LIST OF PUBLICATIONS

1. Zeeshan Salmani and Hualiang Zhang, “Log-periodic array inspired parallel strip Ultra Wideband (UWB) antenna”, published in IEEE Radio and Wireless Symposium (RWS) 2011.
2. Zeeshan Salmani, Yuan Xie, Geng Zheng, Haifeng Zhang, Hualiang Zhang, “Application of Antenna in Strain Measurement,” published in International workshop on Antenna Technology (iWAT) 2011.
3. Zeeshan Salmani, and Hualiang Zhang, “Parallel Strip fed Antenna with extremely wide bandwidth,” (In press) IEEE International Symposium on Antennas and Propagation (APS) 2011.

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