

Aperture Coupled Microstrip Patch Antenna for WIFI, WiMAX, and Radar Applications

by

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Abstract

The aperture-coupled microstrip patch antenna is presented. The operation frequency range of antenna is 4.8 - 5.2 GHz. This frequency range is possible due to the use of low dielectric materials for the patch and microstrip substrate, $\epsilon_r = 1.03$ and $\epsilon_r = 2.6$. The antenna is fed by a microstrip feed line designed for 50Ω impedance. The S_{11} for the antenna at 5 GHz is -38.3 dB. The -10dB bandwidth of the antenna exceeds 400 MHz which equates to 8% bandwidth overall. The realized gain for the antenna at 5 GHz is 8.33 dB when $\theta = 0^\circ$ and $\phi = 90^\circ$. The maximum sidelobes are -3.02 dB and -2.29 dB when $\theta = -55^\circ$ and $\theta = 55^\circ$, respectively. The sidelobe level or the difference between the main beam maximum and the sidelobe, equals to around 10.62 dB. The co-polarization radiation is above -4 dB while the cross-polarization is below -32 dB. The overall performance is sufficient to support WIFI, WiMAX, and radar applications in mobile devices, routers, electronic devices, and for military purposes.

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Chapter 1 Introduction

History of Microstrip Patch Antennas

The idea of microstrip radiators was first mentioned by Deschamps in 1953 and later patented by Gutton and Baissinot in 1955 [1]. The concept and development of microstrip patch antennas was later introduced to the antenna engineering community in the early 1970s. Howell and Munson were the first documented researchers to fabricate a microstrip patch antenna. During the early stages of its development, the microstrip patch antenna received skepticism from researchers due to its extremely narrow bandwidth (around 1-2%) which is unsuitable for wireless communication systems [2]. During this time, two methods were developed to calculate the input impedance response and model the microstrip patch antenna: the transmission line model and the cavity model. Even though these analytical techniques were revolutionary, both techniques were limited in their ability to precisely calculate the performance of the microstrip patch.

As research and development continued into the 1980s, design and analytical techniques for microstrip patch antennas also progressed. Phased array microstrip patch antennas were analyzed in order to explore their overall size limitations [1]. Circular polarization and other polarization methods for microstrip patch antennas were also examined during this period. Many of the major concerns regarding the practicality of microstrip patch were either resolved or under investigation by the end of the 1980s.

By the start of the 1990s, microstrip patch antennas were being implemented into commercial applications such as mobile communication technology [2]. More advanced computation tools such as finite difference time domain (FDTD) and finite element

method (FEM) were capable of evaluating external environments and microstrip patch issues faster than previous computational tools. Due to these more sophisticated computational methods, impedance bandwidth enhancements up to an octave (67%) were produced. Other advancements include multiband microstrip patches, efficient printed antennas, high-gain printed patch antennas, and size reduction techniques for patch conductors.

History of Aperture-Coupled Microstrip Patch Antenna

Aperture coupled microstrip patch antennas have become a viable option for wireless and telecommunication systems over traditional microstrip patch antennas. Research and development in the 1980s contributed to the discovery of the aperture-coupled microstrip patch antenna [2]. David Pozar is credited as being one the main pioneers in the development of the aperture coupled microstrip patch antenna.

The fundamental structural difference between the microstrip patch and aperture coupled microstrip patch antenna is the feed method used to excite the patch. While the microstrip patch antenna uses direct feed in order to excite the patch, the aperture coupled microstrip patch antenna uses non-contact feed lines which is accurately described as the magnetic equivalent of the edge-fed procedure in [2]. The non-contact feed is also capacitive in nature which counteracts with the natural high inductance of the excitation. Having indirect feed contact allowed for the aperture coupled microstrip patch antenna to achieve low current discontinuity which is fundamental for achieving good impedance and radiation performance.

Since its introduction, aperture coupled microstrip antennas have continually been used in numerous applications requiring a wideband frequency range. This includes, but is not limited to, global positioning satellites, cellular phones, personal communications systems, GSM, wireless local area networks, cellular video, direct broadcast satellites, automatic toll collections, collision avoidance radar, and wide area computer networks [3].

Chapter 2 Microstrip Patch Antennas

Design Specifications

A traditional microstrip patch antenna consists of a microstrip line fed directly to a patch resting on a single layer dielectric substrate. A ground substrate is also added to the lower dielectric substrate which serves as a path for return currents. The microstrip patch is considered a resonant type radiator meaning that its feed length is approximately half of the guided wavelength [4]. Figure 1 shows the basic schematic diagram of an edge-fed microstrip antenna.

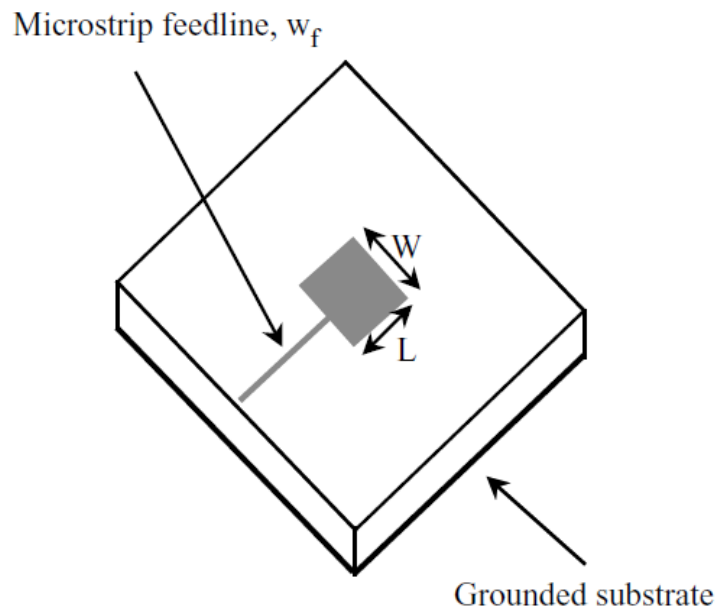


Figure 1. Schematic diagram of a microstrip patch antenna.

The microstrip transmission line is designed to transmit electromagnetic energy to the radiating patch. Figure 2 shows the schematic diagram of a traditional microstrip transmission line.

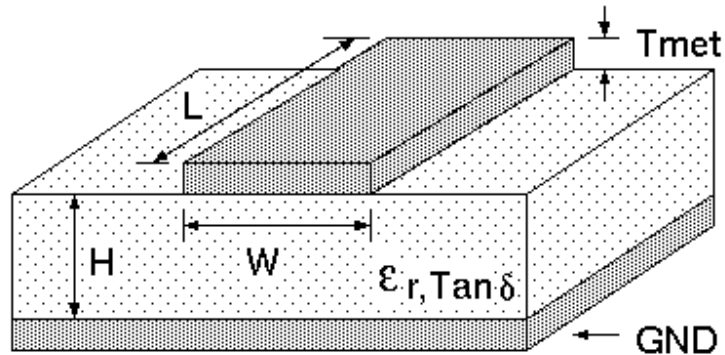


Figure 2. Schematic diagram of a microstrip transmission line.

When designing the microstrip transmission line for an antenna, three design rules must be considered. First, the length of the microstrip transmission line L must be half the guided wavelength of the desired resonant frequency. (Eq. 1) A half guided wavelength is recommended for the length because the current will be excited on the patch and vertical electric fields will be generated between the patch and the ground plane [2]. This effect will cause the radiated fields to add constructively creating an efficient, resonant radiator [2]. Second, the dielectric constant ϵ_r should be as low as possible. The reason is because the permittivity of the dielectric substrate affects the intensity of fringe fields which directly relates to the radiation of the antenna [1]. Typical permittivity values ($\epsilon_r \leq 10$) for microstrip patch antennas vary depending on the substrate's availability, application, and costs. However, the permittivity should be as low as possible ($\epsilon_r \leq 2.5$) in order to increase the strength of fringe fields. Third, a thicker substrate should be used. Even though a thicker substrate h is recommended, the designer should make sure to keep it below a fraction of a wavelength. The substrate thickness h along with the transmission line width w determines the characteristic

impedance Z_o . Equations 1-3 show the mathematical calculations used for microstrip transmission line design [5].

$$\text{Microstrip length} = \frac{\lambda_g}{2} \text{ where } \lambda_g \text{ is the guided wavelength } (\lambda_g = \frac{c}{\sqrt{\epsilon_{eff}}}) \quad (1)$$

$$\text{Effective permittivity} = \epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2\sqrt{1 + \frac{12h}{w}}} \quad (2)$$

$$\text{Characteristic impedance} = \begin{cases} Z_o = \frac{60}{\sqrt{\epsilon_{eff}}} \ln \left(\frac{8h}{w} + \frac{w}{4h} \right) \Omega \text{ for } \frac{w}{h} \leq 1 \\ Z_o = \frac{1}{\sqrt{\epsilon_{eff}}} \frac{120\pi}{\frac{w}{h} + 1.393 + 0.667 \ln \left(\frac{w}{h} + 1.444 \right)} \Omega \text{ for } \frac{w}{h} > 1 \end{cases} \quad (3)$$

The patch element is crucial in the overall performance of the microstrip antenna. The patch's length controls the resonant frequency and the width of the patch affects the resonance impedance level and bandwidth [2]. These conditions are only plausible as long as the dielectric substrate thickness remains below $0.03\lambda_o$. Equations 4-8 show the mathematical equations used to calculate the patch length L and width W [6].

$$Z_o = \frac{120\pi h}{W\sqrt{\epsilon_{eff}}} \quad (4)$$

$$\Delta l = 0.412h \left(\frac{\epsilon_{eff} + 0.3}{\epsilon_{eff} - 0.258} \right)^{\frac{(W/h) + 0.264}{(W/h) + 0.8}} \quad (5)$$

$$f_r = \frac{c}{2\sqrt{\epsilon_{eff}}(L + 2\Delta l)} \quad (6)$$

$$W = \frac{c}{2f_r} \left(\frac{\epsilon_r + 1}{2} \right)^{-1/2} \quad (7)$$

$$(L + 2\Delta l) = \frac{\lambda_g}{2} = \frac{\lambda_o}{2\sqrt{\epsilon_{eff}}} \quad (8)$$

Advantages

Since its discovery, microstrip patch antennas have been continually researched and developed in order to improve its reliability and efficiency. Major advantages of the microstrip patch antenna are its low profile, conformal nature, low production cost, compatibility with microwave integrated circuits, capability to be easily formed into arrays, and efficiency [1-2, 4]. The remainder of this section will further discuss each advantage previously mentioned.

Since most wireless and telecommunications applications require compact components, low profile designs are becoming the standard in the antenna community. Typical substrate layer thickness for a single layer microstrip patch antenna is no more than five-hundredths of a wavelength while the substrate thickness for a multilayer microstrip patch antennas is no more than a tenth of a wavelength [2]. Having minimal substrate thickness allows for easy integration into various applications such as airplanes, consumer electronics, military weaponry, etc.

Being conformal, or flexible, is an advantage of the microstrip patch antenna. Several military applications such as missile guidance systems and aircraft communications require rugged antennas. Soft laminates are used for the dielectric substrate of the microstrip patch allowing it to be easily molded to the body of the missiles or aircrafts [2].

Since standard printed circuit etching techniques are used to create microstrip patch antennas, production costs are relatively low [2]. Using printed circuit methods allows for the entire antenna including the patch and feed to be built in one process which also

significantly reduces manufacturing time and costs. By utilizing printed circuit techniques, microwave integrated circuits are easily integrated with microstrip patch antennas. Standard printed circuit board materials such as FR4 can be used for applications requiring an operation frequency less than 1 GHz [2].

Since microstrip patch antennas are low-gain antennas (less than 8dBi), antenna arrays are necessary in applications requiring a high amount of gain [2]. The manufacturing process for microstrip patch arrays is relatively simple since it is possible to fabricate the entire array network on a single layer. Also, the production cost of multiple antenna elements does not increase significantly, allowing for use in numerous commercial applications.

Essentially, a microstrip patch antenna is an efficient radiator [2]. Due to its resonant nature, the efficiency of a microstrip patch antenna is greater than its wideband variants. Three loss mechanisms contribute to decreased efficiency: conductor loss, dielectric loss, and surface wave loss [2]. In order to minimize loss and maximize efficiency, it is recommended to use direct contact feed techniques rather than non-contact methods. Using a thin, low permittivity substrate will also improve the overall efficiency of the antenna. Figure 3 shows efficiency versus the substrate thickness based on the substrate permittivity [4].

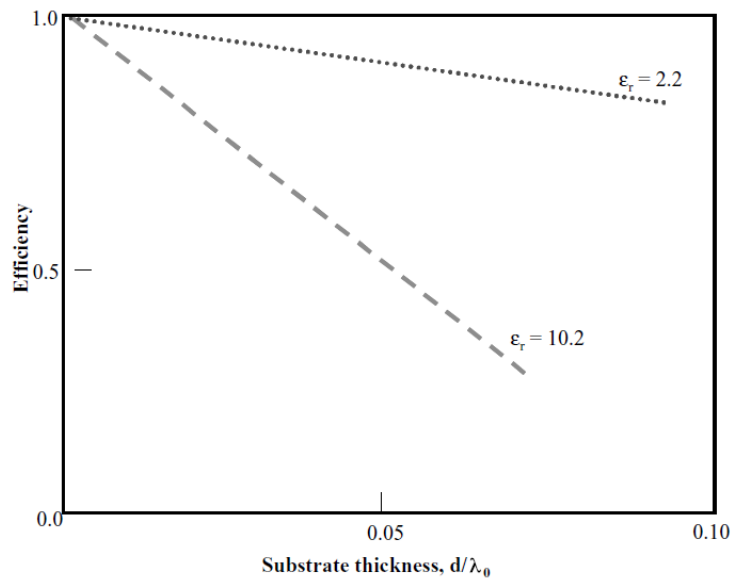


Figure 3. Efficiency versus substrate thickness for microstrip patch antenna.

Disadvantages

Even though the microstrip patch has a wide array of advantages, many disadvantages hinder its use in numerous applications. Some disadvantages of microstrip patch antennas include narrow impedance bandwidth, spurious feed radiation, and poor polarization purity [4, 7]. The remainder of this section will further discuss each disadvantage previously mentioned.

The narrow impedance bandwidth issues are due to the highly inductive nature of the method used to excite the microstrip patch antenna [2]. As the feed line is excited, the frequency response is dominated by a high level of inductance at frequencies below resonance. The microstrip patch antenna is a resonant-styled antenna meaning the reactance of the impedance must equal zero. Therefore, the capacitance and inductance must cancel for optimum performance. The excess inductance reduces the substrate

thickness which reduces the overall impedance bandwidth. Figure 4 shows a plot the bandwidth versus substrate thickness based on the substrate permittivity [4].

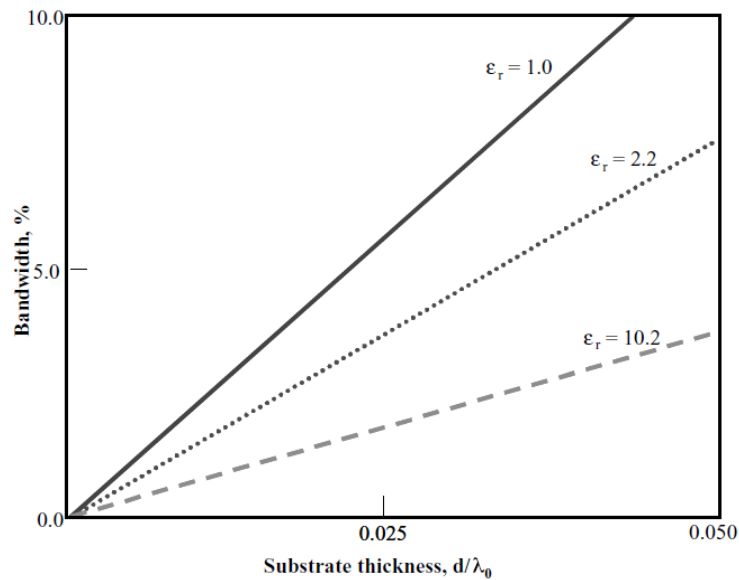


Figure 4. Bandwidth versus substrate thickness for microstrip patch antenna.

Poor polarization is the product of high levels of cross-polarization and mutual coupling within the microstrip patch antenna [1]. Cross-polarization radiation is the radiation field that is produced from the antenna in the opposite direction of the desired radiation field. For example, if the desired field is meant to radiate horizontally, then the cross-polarization field will radiate vertically. The increased cross-polarization levels can be attributed to surface waves diffracting off the antenna's finite ground plane [2].

Design Adaptations

Numerous adaptations of the traditional microstrip antenna have occurred over the past several decades. Several design innovations have successfully addressed and resolved some key issues mentioned in the previous section. In [8], a wideband multislot

antenna for broad band wireless applications is presented. Since a microstrip patch antenna is naturally narrowband, the proposed antenna uses three different narrow slots along with a patch-like tuning stub to enhance bandwidth and maintain modest polarization. The antenna was capable of achieving an impedance bandwidth of around 88% from 5.1 to 13.GHz. Figure 5 shows the geometry of the wideband multislot patch antenna.

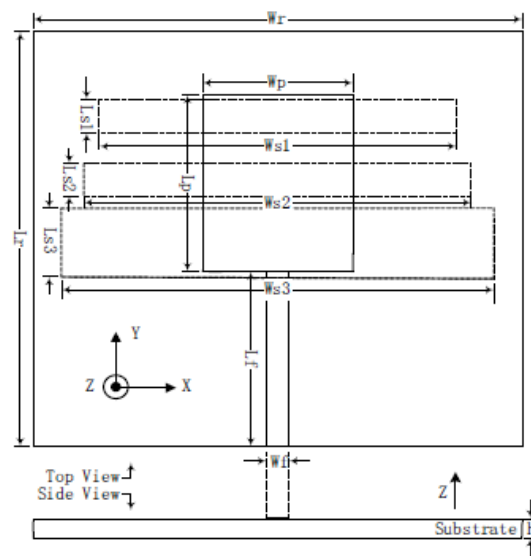
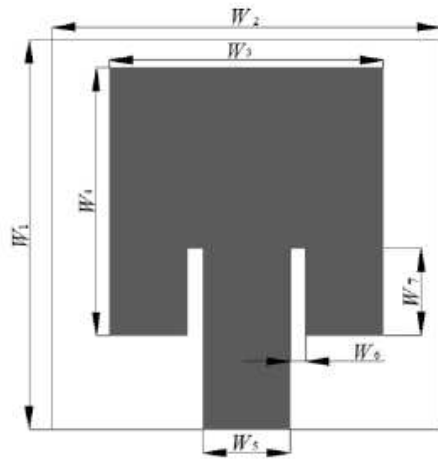
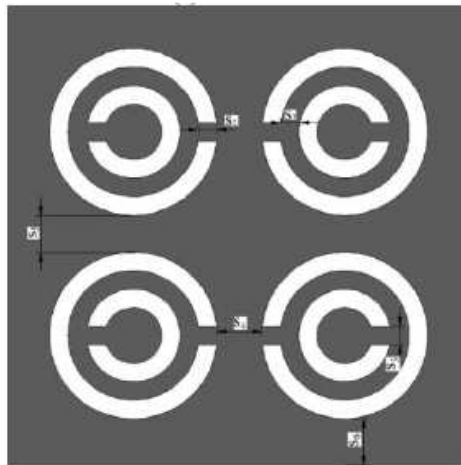


Figure 5. Geometry of the wideband multislot patch antenna.

In [9], a novel, compact printed patch antenna for WiMAX applications was presented. The unique innovation about this design is the designer's ability to reduce the size of the antenna by adjusting the complimentary split ring resonators (CSRR) etched into the ground plane. The reported frequency band and gain are 5.405-5.595GHz and 6.4dBi, respectively. Figure 6 shows the geometry of the compact printed patch antenna.



(a)



(b)

Figure 6. Geometry of the compact printed patch antenna (a) top view and (b) bottom view.

Chapter 3 Aperture Coupled Microstrip Patch Antenna

Design Specifications

Figure 7 shows the schematic diagram of an aperture coupled microstrip patch antenna. The dielectric substrates are separated by a ground plane. The aperture in the ground plane allows for electromagnetic coupling to occur between the feed structure and the patch. Equation 9 shows the mathematical expression for the coupling amplitude between the feed structure and patch, where x_0 is the offset of the aperture from the patch edge, M is the magnetic current density, H is the magnetic field, and L is the length of the microstrip feed [1].

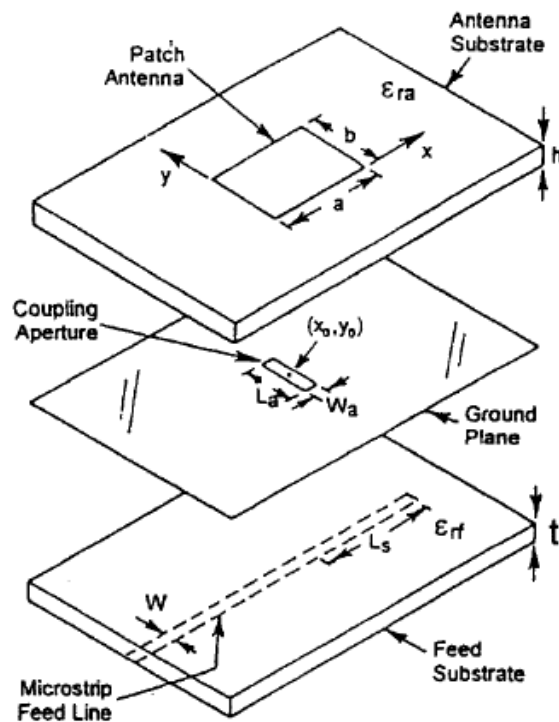


Figure 7. Schematic diagram of an aperture coupled microstrip patch antenna

$$Coupling = \iiint_V M * Hdv = \sin\left(\frac{\pi x_0}{L}\right) \quad (9)$$

Based on circuit theory, the microstrip is seen as an open circuited stub which makes the feed naturally capacitive. The circuit equivalent for an aperture coupled patch antenna is shown in Figure 8.

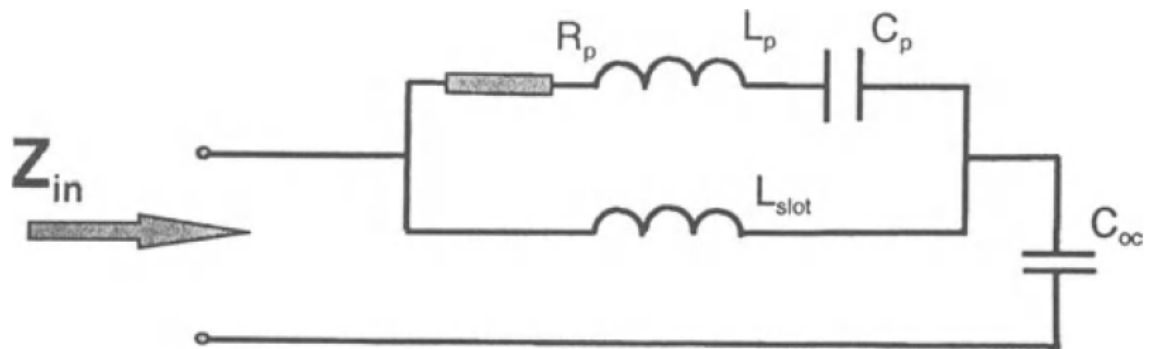


Figure 8. Circuit model for an aperture coupled microstrip patch antenna.

Unlike microstrip patch antennas, aperture coupled microstrip patch antennas have numerous design parameters which allows more degrees of freedom for antenna designers [2]. Design parameters include the antenna substrate, patch dimensions, open circuit stub termination, and slot length. Each of these parameters assists in controlling the outcome of the antenna's input impedance and the front-to-back ratio, which is the ratio of the radiated far-fields in the forward and backwards direction. The remainder of this section will further discuss each design parameter previously mentioned.

The patch substrate is responsible for controlling the bandwidth, radiation efficiency, and coupling level of the antenna [3]. A thick, low permittivity substrate is ideal because it will increase the impedance bandwidth while reducing the surface wave excitation.

The main disadvantage of using a thick, low permittivity substrate is the decrease in coupling for a given aperture size. The mathematical calculations for the patch substrate are shown in Equations 4-8.

The patch dimensions are responsible for dictating the resonant frequency, resonant resistance, and polarization levels [3]. Increasing the patch length will decrease the resonant frequency [1]. The patch width controls the resonant resistance. If a lower resonant resistance is desired, a wider patch is required. If the antenna is critically coupled, minimizing the patch width will result in over-coupling which decreases the front-to-back ratio. This reduction in the front-to-back ratio occurs because the slot becomes larger as the patch size decreases resulting in the slot radiating equally on both sides of the ground plane [1].

The open circuit stub termination is used to match the input impedance response [2]. Adjusting the stub helps tune the excess reactance produced from the slot [3]. Typically, the stub length L_s is less than $\frac{\lambda_g}{4}$ in length. When the stub is shortened, the impedance locus on the Smith Chart will move in the capacitive direction; when the stub is lengthened, the impedance locus will move in the inductive direction.

The slot length controls the size of the impedance locus on the Smith Chart [3]. Increasing the slot length will cause the diameter of the locus to increase consequently making the impedance bandwidth increase. For optimum matching, the locus needs to be large enough to pass through the center of the Smith Chart. To prevent over coupling, the designer must only make the slot length no larger than required.

Advantages

The aperture coupled microstrip patch antenna has several advantages comparable to the edge-fed microstrip patch antenna. Advantages of the aperture couple microstrip patch antenna include wide impedance bandwidth, low cost, compact profile, and very pure radiation [2,3]. The remainder of this section will further discuss each advantage previously mentioned.

Wide impedance bandwidth is the primary benefit of the aperture coupled microstrip patch antenna design. The wideband characteristics are a product of coupled resonances referred to as mutual resonance [2]. Whenever overcoupling occurs to the microstrip feed structure with a low-Q resonance of the patch, an impedance loci is produced on the Smith Chart [2]. In order to optimize the wide bandwidth capabilities, a large impedance locus is desired meaning multiple resonances must be produced.

Pure radiation allows for minimal cross-polarization levels [2]. Since the aperture coupled patch is excited using a thin slot, cross-polarized current are reduced. The major issue that occurs with a thin slot is the increased occurrence of diffracted fields interacting with the finite sized ground plane [2].

Compact profile and low cost advantages of the aperture coupled microstrip patch antenna are similar to the microstrip patch antenna. The only major cost and profile difference is a result of the additional substrate layer between the aperture ground plane and the patch. Current printed circuit technologies are capable of fabricating the feed line on one layer and the radiating patch on a layer within close proximity to it without increasing manufacturing cost [2].

Disadvantages

One disadvantage of aperture coupled microstrip antennas is the multilayer fabrication process. Issues such as patch alignment, small gaps between dielectric layers, and material bonding can significantly alter the performance of the antenna [4]. Small gaps between dielectric layers would change the antenna's input impedance and bandwidth.

Another disadvantage is the possibility of a poor front to back ratio. This issue is a consequence of using a large aperture in order to increase impedance bandwidth. Since the fields from the ground aperture radiates towards the upper (patch) and lower (feed) half, a chance of high backward radiation can occur [4]. High backward radiation can lead to lower power availability in the power budget which is important for communication systems. In order to resolve the issue, the addition of a cavity-backed substrate and/or reflector has been used to decrease the amount of backward radiation from the large aperture.

Scalping of the radiation pattern is another concern when using a large aperture design. Whenever a large aperture is combined with a small ground plane, the radiated power, specifically the electric field, can easily be diffracted off of the ground plane resulting in an altered radiation pattern [4]. In order to avoid this issue, the ground plane should be at least a couple wavelengths large in respect to the center of the patch and slot. The use of absorbing material around the edges of the ground plane also will reduce radiation scalping.

Design Adaptations

Since its introduction into the antenna community, several adaptations of the aperture coupled microstrip antenna have been implemented in order to increase gain, directivity, and bandwidth. The remainder of this section will discuss various design adaptations with their results.

In [1], the aperture coupled stacked patch microstrip antenna is presented. Figure 9 shows the schematic diagram of the aperture coupled stacked patch microstrip antenna. In this configuration, impedance bandwidths up to 70% have been achieved which is relatively high for a microstrip antenna [2]. The increased impedance bandwidth is due to the additional patch which excites additional resonances by increasing electromagnetic coupling.

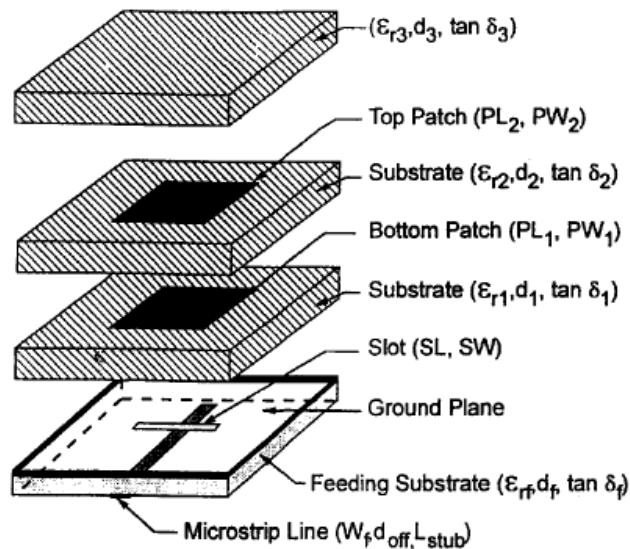


Figure 9. Schematic diagram of the aperture coupled stacked patch microstrip antenna.

In [10], the author improved the bandwidth of the antenna by adding a cavity-backed substrate and a lower ground plane as shown in Figure 10. These design alterations allowed for an increase in coupling between the aperture and patch resulting in a 40% 10dB bandwidth and lower back radiation.

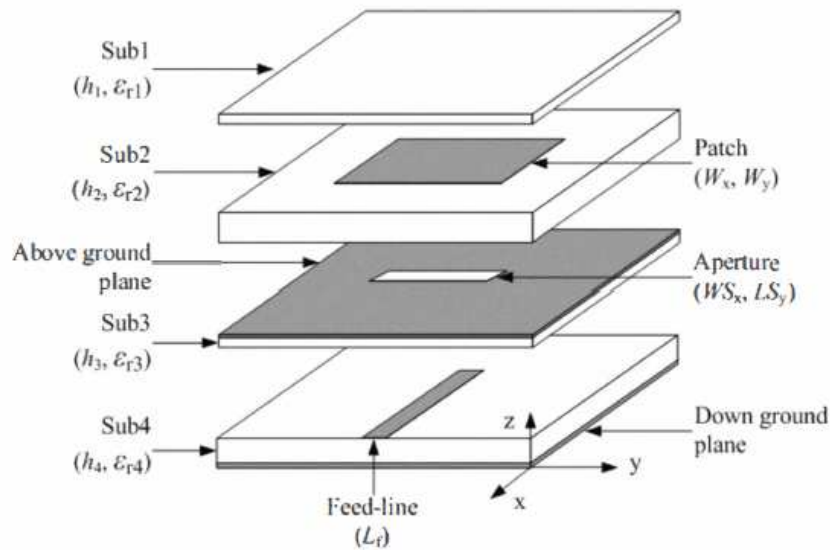
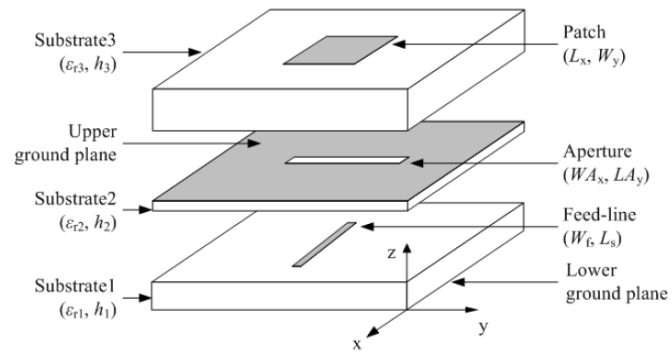
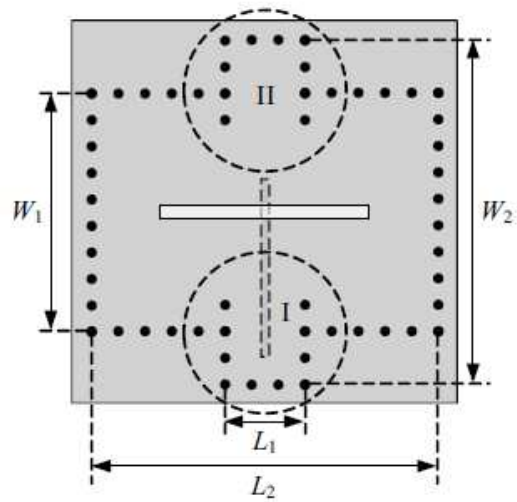


Figure 10. Schematic diagram of the cavity-backed aperture coupled microstrip patch antenna.

In [11], the backed substrate integrated cavity aperture coupled microstrip antenna is introduced. This antenna is an innovative design because it uses metallic vias along with the shape of the backed substrate integrated cavity in order to improve coupling between the patch and aperture. A reported 48% bandwidth was produced along with size reductions. Figure 11 shows the schematic design backed substrate integrated cavity patch with the cross shaped metallic via geometry.



(a)



(b)

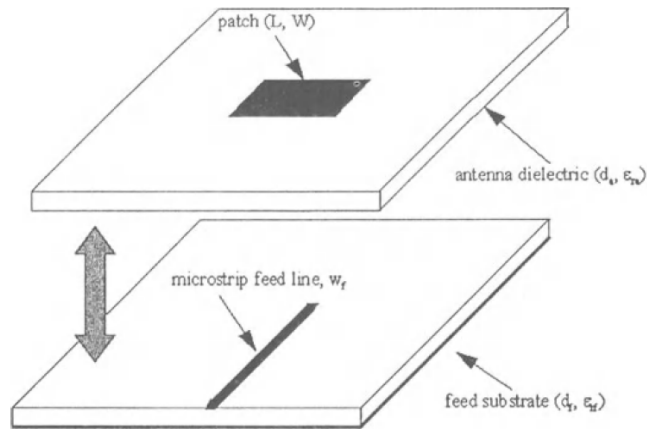
Figure 11. Schematic diagram of the (a) backed substrate integrated cavity aperture coupled microstrip antenna and (b) geometry of the cross shape metallic via configuration.

Chapter 4 Feed Techniques

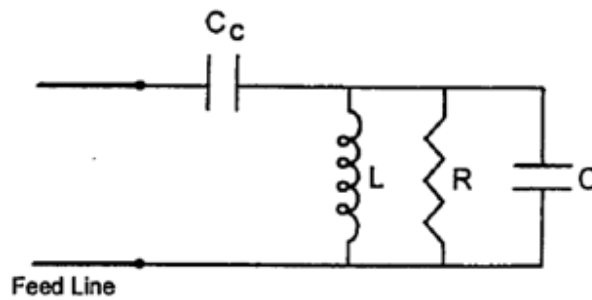
Microstrip feed lines are not the only type of feed lines used with aperture coupled patch antennas. Proximity coupled, stripline, and coplanar waveguide feed substrates have been used in numerous designs in order to achieve improved impedance bandwidth, directivity, and gain. The remainder of this section will discuss in detail the feed techniques mentioned above.

Proximity Coupled Feed

Proximity coupled feed is another non-contacting feed technique similar to the aperture coupled microstrip method. It consists of two substrate layers where the microstrip feed is on the bottom layer and the patch is on the upper layer [1]. The microstrip feed is an open end transmission line making it naturally capacitive. In order to increase bandwidth and reduce the spurious radiation effect from the open end microstrip feed, the substrate characteristics of the two layers must be chosen carefully. Typically, the lower substrate layer is relatively thin in order to manage coupling. Since the patch is placed between two substrate layers, the bandwidth increases dramatically. The downside of this antenna configuration is the fabrication process since accurate alignment of the patch and feed line is crucial. Figure 12 shows the schematic diagram and circuit equivalent model for the proximity coupled fed patch antenna [1, 2].



(a)



(b)

Figure 12. Proximity coupled fed patch antenna (a) schematic diagram and (b) circuit equivalent model.

Stripline Feed

A typical stripline-fed aperture coupled patch antenna consists of a stripline feed placed in between two dielectric substrates with a ground plane placed on the lower dielectric substrate. Figure 13 shows an example schematic diagram of a stripline-fed aperture coupled patch antenna [12].

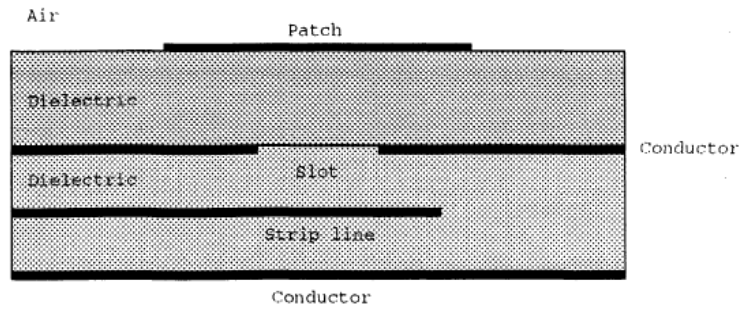


Figure 13. Schematic diagram of stripline-fed aperture coupled patch antenna.

Parallel plate modes are excited primarily by the coupling slot making the stripline feed negligible when considering a symmetric structure [13]. In order to obtain optimum efficiency, the spacing between the coupling slot and ground plane must be half a wavelength. This specific spacing is below the high order modes cut-off frequency. Since size constraints are a factor for practical applications, a substrate thickness of around a quarter wavelengths is expected and produces good results.

In regards to design importance, the patch dimensions have a more dominant effect on the overall performance of the antenna than the slot dimensions [13]. Since the distance between the slot and patch control the coupling, this spacing determines the maximum efficiency. The patch length primarily controls the center frequency resonance. Along with dictating the center frequency, the patch element heavily influences the impedance bandwidth, input impedance and radiation properties of the antenna.

In [13], a stripline-fed aperture coupled double patch antenna was presented. The bandwidth and efficiency of double patch antenna is greater than a single patch design. Similar to the aperture coupled stacked patch microstrip antenna, the upper patch acts as

the radiating element while the lower patch is used to increase coupling. Figure 14 shows the schematic diagram of the stripline-fed aperture coupled double patch antenna.

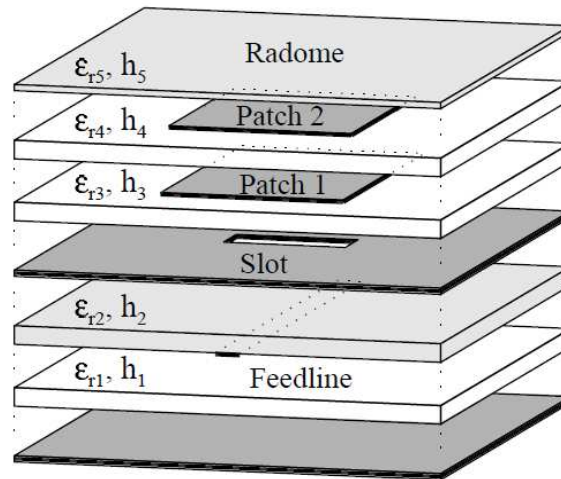


Figure 14. Schematic diagram of stripline-fed aperture coupled double patch antenna.

Coplanar Waveguide Feed

Coplanar waveguide (CPW) feed substrates are an efficient method used to integrate the antenna with monolithic microwave integrated circuits (MMIC). [2] Two methods of excitations have been investigated using a CPW feed. The first method involves the CPW's center conductor splitting the coupling slot into two. The second method changes the CPW into a slot which makes the coupling between the patch and CPW inductive. The primary advantage of a CPW feed is the feed's negligible radiation due to the odd mode excitation of the coupled slot line [2]. Figure 15 shows a schematic diagram of a CPW-fed aperture coupled patch antenna [2].

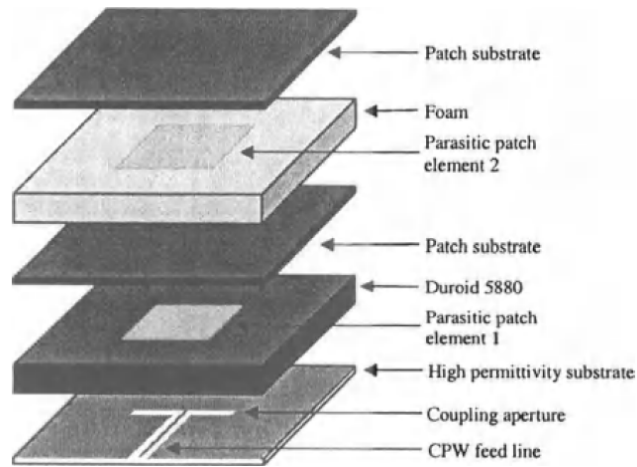


Figure 15. Schematic diagram of a CPW-fed aperture coupled patch antenna.

In [14], a unique broadband coplanar waveguide fed aperture coupled patch antenna using a metamaterial based superstrate is presented. In this design, high directivity and bandwidth is achieved using an array of frequency selective superstrate (FSS) structures to construct the patch. The CPW feed is used to increase wideband performance of the antenna. Figure 16 shows the cross sectional view of the proposed antenna along with the FSS patch array and CPW feed. In this configuration, the antenna achieved an impedance bandwidth in excess of 50% and directivity of about 13.6 dBi.

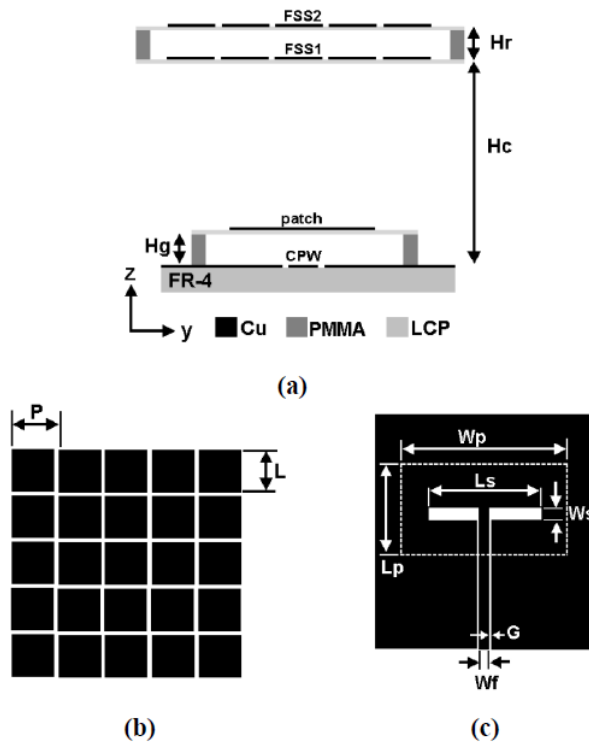


Figure 16. Schematic diagrams of broadband coplanar waveguide fed aperture coupled patch antenna (a) cross-sectional view (b) FSS patch array and (c) CPW feed.

Chapter 5 Aperture Coupled Microstrip Patch Antenna

Applications

WiMAX

WiMAX was created in order to increase broadband communication over a wide network area. In recent years, WiMAX has developed as the standard for present digital networks with a greater range of services [15]. Since its introduction by the industry group WiMAX forum in June 2001, WiMAX has grown from a communication theory to a reliable source for wireless broadband access networks [16]. Formally, WiMAX is a wireless Ethernet alternative to wire technologies (i.e. cable modems, DSL, etc.) which provides broadband access to desired customers. WiMAX was originally developed in order to provide a low-cost alternative for fixed and mobile services (i.e. Voice Over Internet Protocol [VoIP], Information Technology and Video). Unlike WiFi which only offers wireless connectivity for a small coverage area, WiMAX is capable of providing coverage to a large area (around 50km) while supplying bandwidth speeds up to 72 Mbps to users. Two different versions of WiMAX were established in order to optimize the overall performance of WiMAX network. The first version is IEEE 802.16-2004 which provides fixed and nomadic access to WiMAX networks. The second version is IEEE 802.16e which provides network support for portable and mobile communication electronics. The initial frequency profiles that have been developed for mobile applications for WiMAX are 2.3, 2.5, 3.5, and 5.1-5.8 GHz [17]. Each WiMAX version will be discussed in further detail in the remainder of this section.

IEEE 802.16-2004 and IEEE 802.16e Standards

The IEEE802.16 standard is used to supply coverage over large wireless metropolitan area networks (WMAN) [16]. It includes the Physical (PHY) and Medium Access Control (MAC) layers. It uses both Point-to-Multi-Point (PMP) and Mesh modes in order to communicate between subscriber stations and the base station. The difference between PMP and Mesh modes is that in PMP mode, two subscriber stations can only correspond with each other through the base station; while in Mesh mode, two subscriber stations are allowed to communicate directly with each other. Both PHY and MAC layers implement the PMP and mesh mode when transmitting information to one another.

The main modulation techniques used in transmitting information to end-users are orthogonal frequency division multiplexing (OFDM) and orthogonal frequency division multiplexing access (OFDMA). Based on the amount of noise and the transmission distance, both of these methods provide adaptive modulation to available subscribers. By using these methods effectively, WiMAX is capable of supporting fast-speed mobile communications at a higher spectral efficiency while reducing the amount of external interference.

The IEEE 802.16e-2005 standard was completed in February 2005 in order to supply high-speed mobile support for subscriber stations [16]. Two major issues occurred when attempting to add mobile access that forced many changes to PHY and MAC layer in order to establish mobility support. The first issue was the handover, which manages base station switching and handoff methods for inter-cell and inter-sector handover between multiple sized cells. The second issue was power management which consisted of taking advantage of two modes of operation in order to reduce mobile power

consumption: idle and sleep mode. Once these problems were resolved, IEEE 802.16e-2205 was ready to be employed in current generation technology.

Impact of WiMAX Technology

The overall impact of WiMAX into the consumer market has been substantial. Based on [18], WiMAX has become a more advantageous alternative to current 3G systems due to the fact that its frequency spectrum is cheaper, it is 100 percent IP based, has a higher quality of service (QoS) and data rate, is an open system, and it is acceptable to the large developing country markets. The need for WiMAX broadband service has increased from around 430 million customers in 2009 to nearly 800 million consumers in 2010 worldwide, which is nearly double the market coverage for mobile users.

This exponential growth for reliable broadband services has contributed to a rise in portable internet-accessible devices such as laptops, mobile phones, and tablet computers. Even though laptops are still the major medium for access to the internet, mobile phones and tablet computers have gained popularity among end-users. Most present-day technology giants have begun including WiMAX into their mobile chipsets. For example, Intel introduced the Intel WiMAX Connection 2300 chipset in December 2006 which includes mobile WiMAX and Wi-Fi [18]. Another example is the Samsung SWD-M1000 Mondri, which was the tech giant's first mobile WiMAX enabled handheld device [19]. These two devices are prime examples of the ever-expanding market for WiMAX-enabled devices and WiMAX's relevance in future mobile innovations.

WIFI

WIFI (or IEEE 802.11) was first released in 1997 with the capability to transmit raw data at speeds of 1 and 2 megabits per second (Mbit/s) using the Industrial Scientific Medical (ISM) frequency band at 2.4GHz [20]. Since its original release, the IEEE 802.11 standard has been amended several times in order to increase availability and overall performance. The first amendment was introduced in 1999 as the IEEE 802.11b. IEEE 802.11b increased the raw data rate to 11 Mbit/s using the 2.4 GHz frequency band [20]. Depending on user's desired signal quality, the 11 Mb/s data rate was scaled down to 5.5 Mb/s, 2 Mb/s, and/or 1 Mb/s. The second amendment was the 802.11a standard which was the first standard to operate in the 5 GHz frequency band. Since the 2.4 GHz frequency band has a limited number of non-overlapping channels and is heavily used, the 5 GHz frequency range allows for less interference from other wireless devices such as Bluetooth, computers, and other electronics [21]. The major tradeoff for using the 5 GHz is the reduced network range available meaning propagation through solid obstacles (such as walls, trees, etc.) are decreased significantly.

Radar

Interests in radar applications at the 5 GHz range has increased over the past decade. In 2003, the International Telecommunication Union Radiocommunication Sector (ITU-R) created the sharing criteria for the 5GHz range [22]. One notable radar application in the 5 GHz range is weather radars. Due to their short pulse type and scanning patterns, weather radars are hard to detect in this frequency range.

Chapter 6 High Frequency Structure Simulator Methods

High Frequency Structure Simulator or HFSS is a software program with the ability to calculate the electromagnetic behavior of a structure [23]. It can solve basic open boundary problems, generalized S-parameters, and eigenmodes (resonances) of a structure by using a finite element method (FEM) solver. HFSS designs include, but are not limited to, antennas such as helical, pyramidal horn, and coax fed patch; signal integrity structures such as vias, coax bend transient, and connectors; RF/microwave structures such as bandpass filter, combiner, and tee; and integrated circuits such as package models and spiral inductors.

Absorbing Boundary Conditions

Radiation boundaries, also known as absorbing boundary conditions (ABC), are used to simulate radiating electromagnetic waves in an infinite space [23]. In order to replicate infinite space, HFSS absorbs any radiating waves and infinitely expands the boundary area. This simulation method is useful in antenna design where the near-field and/or far-field patterns assist in determining the performance of an antenna design.

Typically, an ABC effectively absorbs incident energy that is normal to the surface of the radiating element. ABCs are usually placed at least quarter wavelength away from strongly radiating structures for precise simulation results [23]. The distance between the radiating structure is crucial to accurate simulation results.

Perfectly Matched Layer

A perfectly matched layer (PML) boundary is described as a fictitious lossy anisotropic material that fully absorbs electromagnetic fields from radiating elements

[24]. Compared to absorbing boundary conditions, PMLs absorb a wider range of frequency and directional waves at the cost of more computing RAM. This method allows for boundary conditions to be closer to radiating elements resulting in smaller 3-D models [23]. Unlike ABC where the distance between the boundary and the radiating structure is crucial, the boundary distance for PMLs is more flexible.

Chapter 7 Aperture Coupled Microstrip Patch Antenna

Design Specifications

An aperture coupled microstrip patch antenna was created and simulated in HFSS. Figure 17 shows the 3-D schematic of the proposed aperture coupled microstrip patch antenna. Table 1 shows the design parameters used for the aperture coupled microstrip patch antenna.

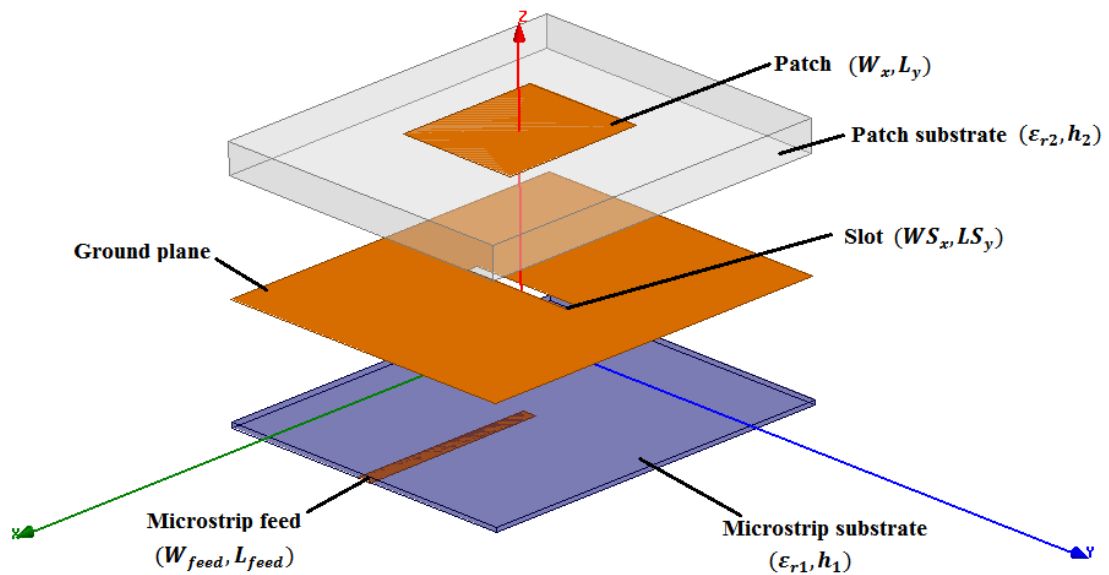


Figure 17. 3-D schematic diagram of aperture coupled microstrip antenna.

Design Parameters		Value (in mm)
Microstrip Substrate Thickness (Arlon AD260A)	h_1	1.016
Patch Substrate Thickness (Eccostock PP-2)	h_2	6.35
Patch Length	L_y	25.5087
Patch Width	W_x	29.7775
Slot Length	LS_y	23.7
Slot Width	WS_x	2.1
Stub Length	l_{stub}	1.5
Microstrip Feed Length	L_{feed}	37.2725
Microstrip Feed Width	W_{feed}	3

Table 1: Design parameters for aperture coupled microstrip patch antenna.

The patch element rests on Emerson & Cuming Eccostock PP-2 polyethylene foam ($\epsilon_{r2} = 1.03$ and loss tangent = 0.0001). As mentioned in previous sections, an ideal substrate for the patch element is one that has a low permittivity and thick substrate for increased bandwidth which Eccostock PP-2 meets both specifications. Additional benefits of this material include lightweight, durability (weather resistant), and ability to return to its normal thickness after being compressed.

The microstrip feed line is placed on Arlon AD260A ($\epsilon_{r1} = 2.6$ and loss tangent = 0.0017). As mentioned in previous sections, the microstrip substrate should have a low permittivity with a relatively thin substrate in order to increase fringing fields which Arlon AD60A meets both specifications. Additional benefits of this material include low insertion loss and high antenna efficiency.

The patch length and width dimensions were determined using Equations 4-8. In order to expedite the calculation process, a MATLAB patch dimension calculator

created by Anurag Ghosh was used. [Appendix 1] The patch dimensions were determined using the known patch substrate thickness, permittivity, and desired resonant frequency. Table 2 shows the calculated and simulated patch dimensions for the antenna. As shown in Table 2, the patch length was lengthened in order to achieve an optimum resonance at 5 GHz.

	Calculated (mm)	Simulated (mm)
Patch Length	20.6622	25.5087
Patch Width	29.7775	29.7775

Table 2. Calculated and simulated patch dimensions.

The slot length and width dimensions were determined using the parametric sweep function in HFSS. According to [3], the ratio of slot width to length is around $\frac{1}{10} = 0.1$. Based on my design, the ratio of slot length to width is $\frac{2.1}{23.7} = 0.09$ which is close to the initial ratio.

The microstrip feed length was determined using information found in [25]. The total feed length for an open-circuit microstrip line is 0.739λ . [25] The stub length is included with the total feed length which is a length of 0.211λ from the center of the slot. Therefore, the feed length from the edge to the center of the slot is 0.528λ . Figure 18 shows a schematic diagram of the nominal HFSS feed and stub length dimensions.

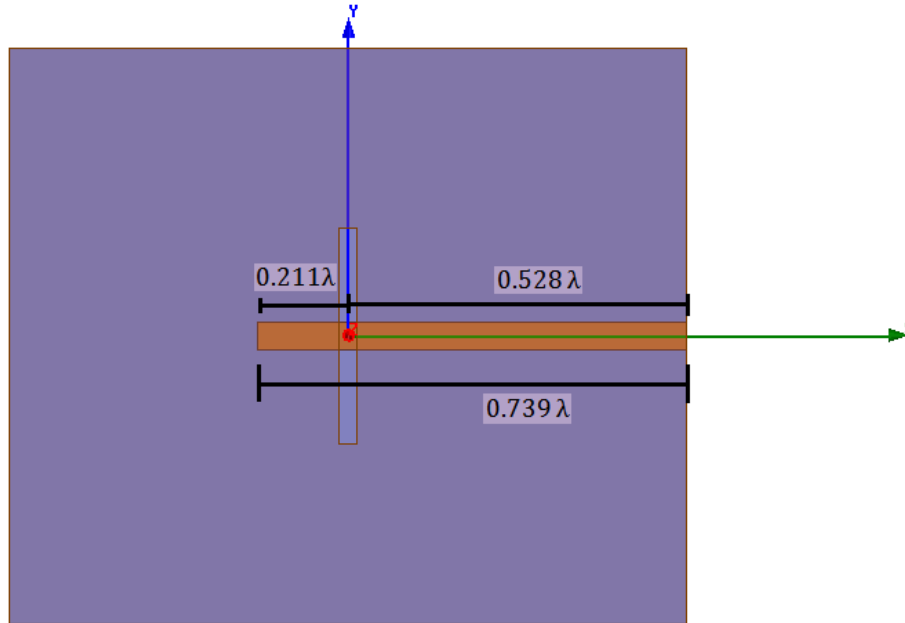


Figure 18. Nominal HFSS feed and stub length dimensions.

Using these nominal HFSS values, the feed and stub lengths were calculated and implemented in the initial design. After conducting a parametric sweep in HFSS, the optimum feed and stub length were determined. Table 3 shows the nominal and simulated feed and stub length at a frequency of 5 GHz. Based on Table 2, the nominal and simulated total feed lengths have a percent difference of 14.35%.

	Nominal (mm)	Simulated (mm)
Feed Length	31.68	37.2725
Stub Length	12.66	1.5
Total Feed Length	44.34	38.7725

Table 3. Nominal and simulated feed, stub, and total length at 5 GHz.

The microstrip feed width was determined using Equation 2. In order to expedite the calculation process, the online microstrip calculator on Microwaves101.com was used

in order to obtain accurate, consistent values. Based on the known substrate thickness and permittivity, the microstrip feed width was calculated to be 3 mm for a substrate thickness of 1.016mm where $\epsilon_{r1} = 2.6$.

As mentioned in Chapter 6, the amount of separation between the antenna structure and the absorbing boundary is crucial for accurate simulation results. Figure 19 shows the side view of the aperture coupled patch antenna with the ABC. When using an absorbing boundary condition (ABC), the distances between both the microstrip feed and radiating element from the ABC is approximately a quarter wavelength as shown in Equation 10 where c is the speed of light, f is the desired frequency, and λ_g . The calculated distance is equal to 14.78mm.

$$\frac{\lambda_g}{4} = \frac{1}{4} \frac{c}{\sqrt{\epsilon_r f}} = \frac{1}{4} \frac{3 \times 10^8 \text{ m/s}}{\sqrt{1.03} * (5 \text{ GHz})} = 14.78 \text{ mm} \quad (10)$$

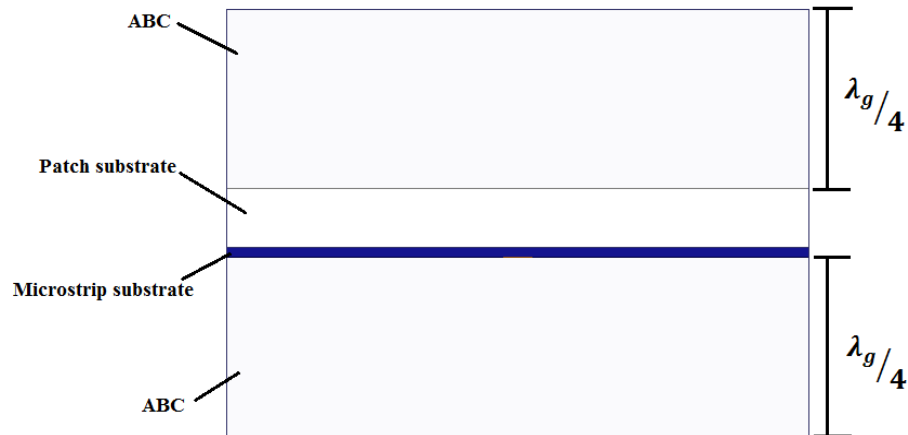


Figure 19. Side view of aperture coupled patch antenna with ABC.

Simulation Results

Figure 20 shows the simulated S_{11} of the aperture coupled microstrip antenna. The -10 dB bandwidth is approximately 400 MHz from 4.8-5.2 GHz. The percent bandwidth achieved from this antenna is around 8% based on Equation 11 where f_H is the highest frequency at -10 dB and f_L is the lowest frequency at -10 dB. One major resonance occurs at the frequency of 5 GHz.

$$\%BW = 2 \frac{f_H - f_L}{f_H + f_L} \times 100 \quad (11)$$

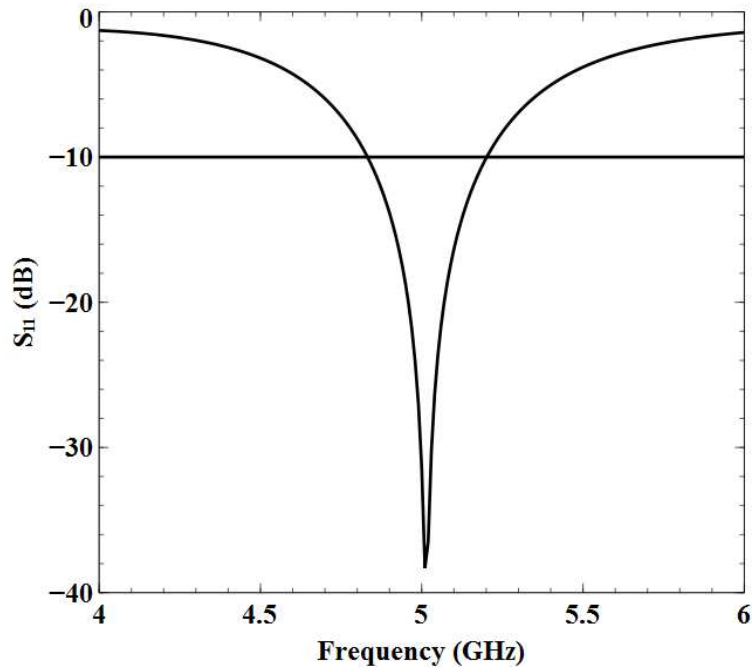


Figure 20. Simulated S_{11} of the aperture coupled microstrip antenna.

Figure 21 shows the Smith Chart impedance locus for the aperture coupled microstrip patch antenna. When the locus passes through the center of the Smith chart, the optimum matching condition has been achieved. Based on the figure, optimum

matching occurs when the frequency is 5 GHz which validates the resonance in Figure 20.

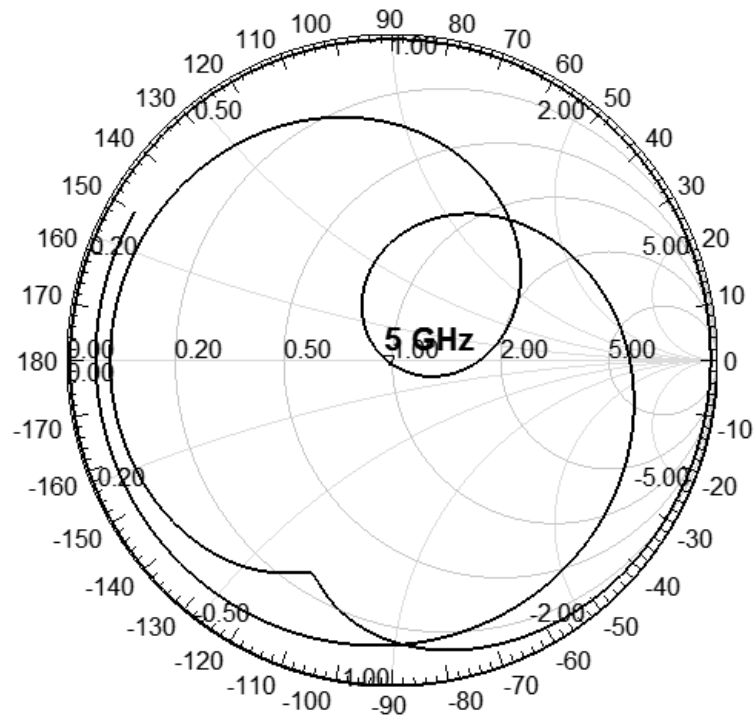


Figure 21. Smith chart for aperture coupled microstrip patch antenna.

The realized gain represents the gain that includes the reflection losses at the input of the antenna. The realized gain is calculated by taking the ratio of the power radiated to the power into the antenna. Figure 22 shows the 3-D plots of the realized gain at 5 GHz. Figure 23 shows the rectangle plot of the realized gain at 5 GHz. As shown in the figures, the maximum realized gain is 8.33 dB at 5 GHz when $\theta = 0$ and $\phi = 90$, respectively. The maximum sidelobes are -3.02 dB and -2.29 dB when $\theta = -55^\circ$ and $\theta = 55^\circ$, respectively. Therefore, the sidelobe level or the difference between the main beam maximum and the sidelobe, equals to around 10.62 dB. Having low sidelobes is

often imperative in antenna design since excessive sidelobe radiation wastes energy and may cause interference to other equipment.

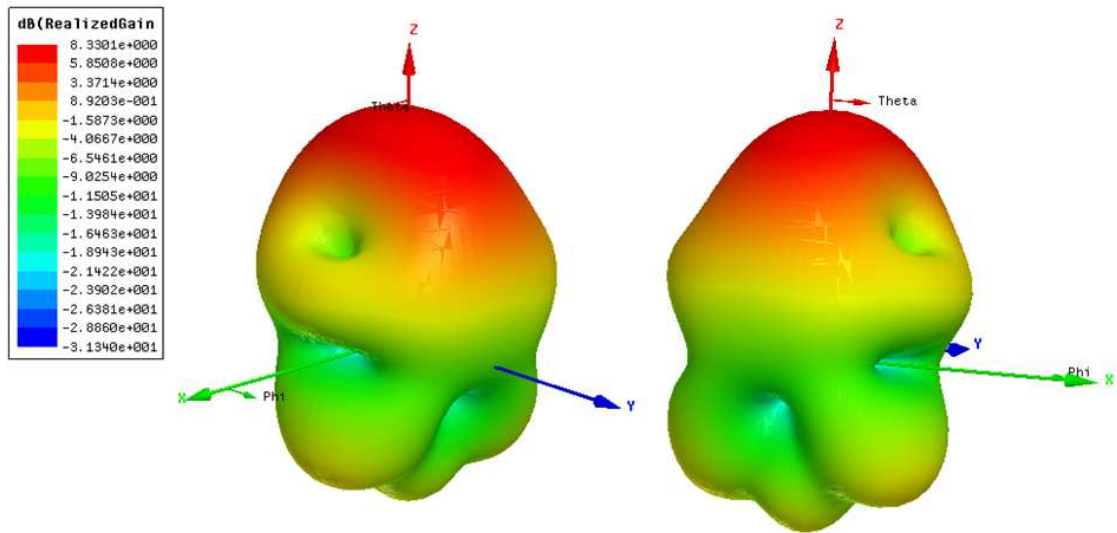


Figure 22. 3-D plots of realized gain for aperture coupled microstrip patch at 5 GHz

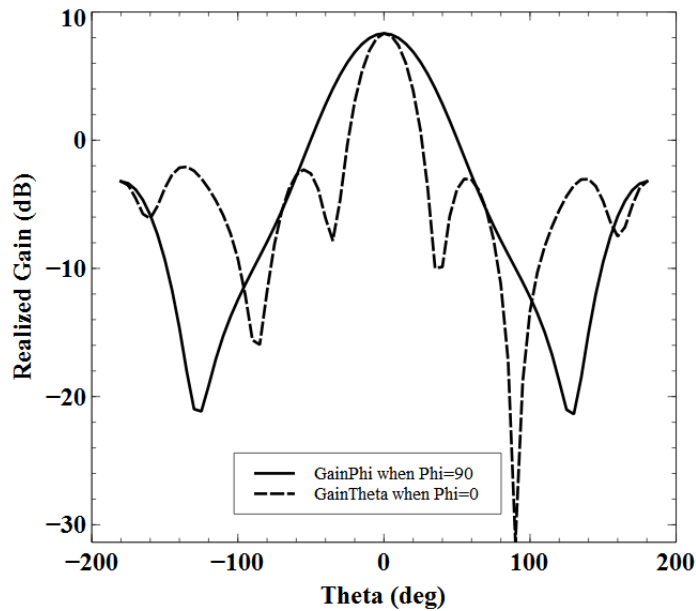


Figure 23. Rectangular plot of realized gain for aperture coupled microstrip patch at 5 GHz.

Figure 24 shows the co-polarization and cross-polarization E-field and H-field patterns at 5 GHz. As described in previous sections, the cross-polarization pattern is desired to be as low as possible in order for the co-polarization pattern to be dominant. As shown in Figure 24, the cross-polarization levels remain below -32 dB while the co-polarization levels remain above -4 dB.

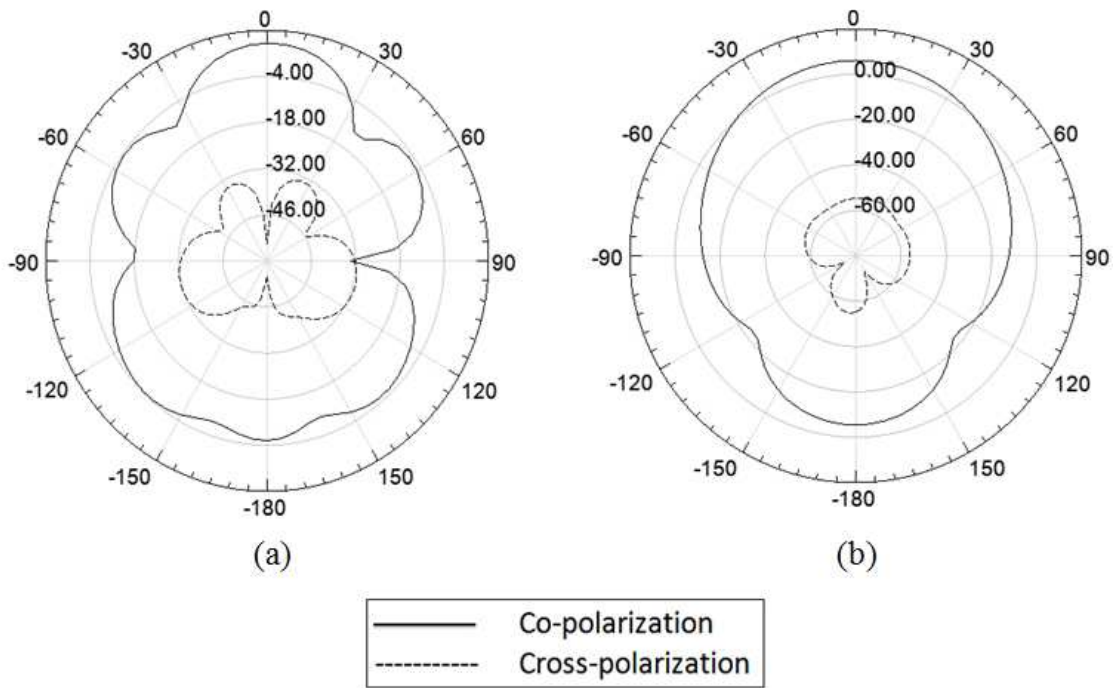


Figure 24. Co and cross polarization for (a) E-plane at 5 GHz (b) H-plane at 5 GHz.

Chapter 8 Conclusion and Future Work

An aperture coupled microstrip patch antenna has been presented. The antenna is capable of operating in the 4.8 – 5.2 GHz range. The S_{11} for the antenna at 5 GHz is -38.3 dB. The -10dB bandwidth exceeds 400 MHz which equates to 8% bandwidth overall. The total realized gain at 5 GHz is 8.33 dB when $\theta = 0^\circ$ and $\phi = 90^\circ$. The maximum sidelobes are -3.02 dB and -2.29 dB when $\theta = -55^\circ$ and $\theta = 55^\circ$, respectively. The sidelobe level equals to around 10.62 dB below the main beam maximum. The co-polarization radiation is above -4 dB while the cross-polarization is below -32 dB which is desired. The designed antenna is capable of supporting WIFI, WiMAX, and radar applications at 5 GHz.

Several modifications could be made in order to maximize the overall performance of the antenna. The bandwidth, realized gain, and size could be greatly improved if various enhancements were applied. The remainder of this section will cover methods that could be implemented in future work.

First, the antenna's bandwidth could be increased if the slot aperture was altered. The H-shaped slot has shown to increase the coupling level between the slot and patch which could excite more resonances. Another method that could be used is to increasing the number of slots in the aperture to produce multiple resonant frequencies. Adding a substrate integrated cavity with metallic vias has also proven to improve the coupling level. The major tradeoff of each of these methods is that the antenna design becomes more intricate and complex causing an increase in both fabrication time and costs.

Second, an array could be used to increase the overall gain of the antenna. Even though the patch antenna has a realized gain of around 8.33 dB, a higher gain may be required for most long-range wireless applications. The main tradeoff of using an array is increased design complexity especially for impedance matching and electromagnetic interference issues. Another method that would increase the gain would be to add a reflector element to the antenna. The reflector element would reduce the amount of back radiation caused by the large aperture slot and therefore would decrease the front to back ratio.

Third, decreasing the size would allow for the antenna to be implemented in more wireless mobile applications where board space is limited. These applications include, but are not limited to, cellular phones, WiFi/WiMAX routers, gaming consoles, weather radars, WiFi-enabled televisions, etc.

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```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Final Year MAJOR Project 2008
% Author-- Anurag Ghosh
% Microstrip Calculator GUI
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
function varargout = untitled(varargin)
% UNTITLED M-file for untitled.fig
% UNTITLED, by itself, creates a new UNTITLED or raises the existing
% singleton*.
%
% H = UNTITLED returns the handle to a new UNTITLED or the handle to
% the existing singleton*.
%
% UNTITLED('CALLBACK',hObject,eventData,handles,...) calls the local
% function named CALLBACK in UNTITLED.M with the given input arguments.
%
% UNTITLED('Property','Value',...) creates a new UNTITLED or raises the
% existing singleton*. Starting from the left, property value pairs are
% applied to the GUI before untitled_OpeningFunction gets called. An
% unrecognized property name or invalid value makes property application
% stop. All inputs are passed to untitled_OpeningFcn via varargin.
%
% *See GUI Options on GUIDE's Tools menu. Choose "GUI allows only one
% instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES
```

```
% Edit the above text to modify the response to help untitled
```

```
% Last Modified by GUIDE v2.5 06-May-2008 02:35:10
```

```
% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name', mfilename, ...
                  'gui_Singleton', gui_Singleton, ...
                  'gui_OpeningFcn', @untitled_OpeningFcn, ...
                  'gui_OutputFcn', @untitled_OutputFcn, ...
                  'gui_LayoutFcn', [] , ...
                  'gui_Callback', []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT
```

```
% --- Executes just before untitled is made visible.
function untitled_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject handle to figure
```

```

% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)
% varargin command line arguments to untitled (see VARARGIN)

% Choose default command line output for untitled
handles.output = hObject;

% Update handles structure
guidata(hObject, handles);

% UIWAIT makes untitled wait for user response (see UIRESUME)
% uiwait(handles.figure1);

% --- Outputs from this function are returned to the command line.
function varargout = untitled_OutputFcn(hObject, eventdata, handles)
% varargout cell array for returning output args (see VARARGOUT);
% hObject handle to figure
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;

% --- Executes during object creation, after setting all properties.
function edit1_CreateFcn(hObject, eventdata, handles)
% hObject handle to edit1 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
% See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(
(0,'defaultUicontrolBackgroundColor'))
set(hObject,'BackgroundColor','white');
end

function edit2_Callback(hObject, eventdata, handles)
% hObject handle to edit2 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit2 as text
% str2double(get(hObject,'String')) returns contents of edit2 as a double

% --- Executes during object creation, after setting all properties.
function edit2_CreateFcn(hObject, eventdata, handles)
% hObject handle to edit2 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.

```

```

%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit3_Callback(hObject, eventdata, handles)
% hObject      handle to edit3 (see GCBO)
% eventdata    reserved - to be defined in a future version of MATLAB
% handles      structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit3 as text
%          str2double(get(hObject,'String')) returns contents of edit3 as a double

% --- Executes during object creation, after setting all properties.
function edit3_CreateFcn(hObject, eventdata, handles)
% hObject      handle to edit3 (see GCBO)
% eventdata    reserved - to be defined in a future version of MATLAB
% handles      empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% --- Executes on button press in pushbutton1.
function pushbutton1_Callback(hObject, eventdata, handles)
freq=str2double(get(handles.edit1,'String'));
er=str2double(get(handles.edit2,'String'));
h=str2double(get(handles.edit3,'String'));
height = h/1000*2.54;
Width=30.0/(2.0*freq)*sqrt(2.0/(er+1.0))*10;
ereff=(er+1.0)/2.0+(er-1)/(2.0*sqrt(1.0+12.0*height/Width));
dl=0.412*height*((ereff+0.3)*(Width/height+0.264))/((ereff-0.258)*(Width/...
    height+0.8));
lamda=30.0/(freq*sqrt(ereff));
lamda0=30.0/freq;
Leff=lamda/2;
L=Leff-2*dl;
Length = L*10;
k0=2*pi*freq/30;
phil=0:360;
thetal=0:180;
phi=phil./180.*pi;
theta=thetal./180.*pi;

Rr=120*lamda0/(1-k0^2*height^2/24);
Radiation_resistance = Rr;

```



```

set(handles.text4,'String',Length);
set(handles.text5,'String',Width);
set(handles.text11,'String',Radiation_resistance);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Radiation patterns
% Plotting of radiation patterns on polar and rectangular co-ordinate system

% Calculating the normalized field values for polar plot
Etheta=sin(k0*height/2.*cos(theta)).*cos(k0*L/2.*cos(theta))/k0/height*...
    2./cos(theta);
Etheta_max=max(Etheta);
Etheta_norm=Etheta./Etheta_max;

Ephi=sin(k0*Width/2.*cos(phi)).*sin(phi)/k0/Width*2./cos(phi);
Ephi_max=max(Ephi);
Ephi_norm=Ephi./Ephi_max;
axes(handles.axes1);
cla;

polar(theta,Etheta_norm,'-r')
hold on;
polar(phi,Ephi_norm,'-b')
title('Radiation plot of E and H plane patterns');
% title('E- and H-plane Patterns of Rectangular Microstrip Antenna',...
%     'fontsize',[12]);
legend('E plane','H plane');

% Space wave, surface wave and gain calculations

k0d=k0*height;

%Space wave power
Psp = 377*k0^2*k0d^2/3/pi*(1-1/erfff+2/5/erfff^2);

%Surface wave power
s=sqrt(erfff-1);
k0ds=k0d*s;
alpha0=s*tan(k0ds);
alpha1=-[tan(k0ds)+k0ds/(cos(k0ds))^2];
x0d=erfff^2-alpha1^2;
x0n=-erfff^2+alpha0*alpha1+erfff*sqrt(erfff^2-2*alpha0*alpha1+alpha0^2);
x0 = 1+x0n/x0d;

Psur = 377*k0^2/4*erfff*(x0^2-1)/[erfff*[1/sqrt(x0^2-1)+sqrt(x0^2-1)/(...
    erfff-x0^2)]+k0d*[1+erfff^2*(x0^2-1)/(erfff-x0^2)]];

Efficiency=Psp/(Psp+Psur);

Gain=10*log10(Efficiency*2*pi*Leff*Width/lamda0);

```

```

set(handles.text14,'String',Efficiency);
set(handles.text15,'String',Gain);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% recessed feedline width
% characteristic impedance

x=30*pi/sqrt(er)/50-0.441;

if sqrt(er)*50 <= 120
    W0=height*x;
else
    W0=height*(0.85-sqrt(0.6-x));
end
% Width_of_microstrip_feed=W0;

if W0/height <= 1
    Z0=60/sqrt(ereff)*log(8*height/W0+W0/4/height);
else
    Z0=120*pi/sqrt(ereff)*inv(W0/height+1.393+.667*log(W0/height+1.444));
end
% characteristic_Impedance = Z0
set(handles.text17,'String',Z0);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% hObject    handle to pushbutton1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% --- Executes during object creation, after setting all properties.
function text1_CreateFcn(hObject, eventdata, handles)
% hObject    handle to text1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

```