0.1 Microstrip Patch Antennas

By introduction of the ground plane and advances in the printed circuit board technology, the two-wire transmission lines were reduced to planar configurations. Planar configurations provided opportunities for realizing new microwave techniques. The advantages of using planar configurations such as microstrip structures include low-cost, low-size, low-weight, and more importantly good electrical and electromagnetic characteristics. A microstrip transmission line is basically evolved from the two-wire transmission line. Fig. 1 shows the parallel wire transmission line concept. If an infinite width ground plane is placed between the two wires, then according to the image theory, the image of the upper conductor will exist at the location of the lower conductor. Consequently, the lower conductor line can be removed. Also, the upper conductor can be replaced with a strip placed on the ground plane while a dielectric layer is sandwiched between the ground plane and the upped conductor, forming a microstrip transmission line **4050884**.

Microstrip patch antennas can be considered as an extension of microstrip transmission lines and were first proposed in **4050884** by Grieg and Englemann in 1952. Fig. 2 shows the geometry of a microstrip patch antenna fed by a microstrip line. Other feeding techniques are also possible, and some of them will be discussed in this dissertation. Similar to microstrip transmission lines, microstrip patch antennas have several desirable characteristics. For instance, the thickness of microstrip patch antennas could be as low as a fraction of an inch. Also, using flexible substrates, conformal antennas whose shapes are conformed by non-electromagnetic requirements are also feasible.

Realizing dual-polarization capability is also possible using microstrip

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Fig. 1: Evolution of a line above ground plane; (a) Two-wire transmission line, (b) One conductor above ground plane, (c) Microstrip transmission line **4050884**.

patch antennas. In fact, the most common type of dual-polarized element, for antenna array applications, is microstrip patch antenna. Compared to a high-performance dipole antenna, it possesses a low profile geometry with less fabrication complexity, especially in the array configurations. In this chapter, an overview of various designs of dual-polarized microstrip patch antennas is presented.

0.2 Dual-Polarized Microstrip Patch Antennas

A dual-polarized patch antenna can be excited using two coaxial feeds placed at two orthogonal points. The coaxial feed ports are located at the Null

Chapters/AntOveView/fig2.pdf

Fig. 2: Microstrip patch antenna configuration.

location of horizontal and vertical polarizations. Therefore, the input impedance of polarization won't be affected by the other polarization feed line. Microstrip patch antennas excited using this method are known as probe-fed (pin-fed) patch antennas. In Ref. **saeidi2016dual** a probe-fed patch antenna is designed, and an isolation level of better than 30 dB is reported.

As shown in Fig. 3 in the probe-fed patch antenna the inner conductor of coaxial feed is connected to radiating patch antenna. However, as shown in Fig. 4, the patch antenna can be excited using capacitive probes, in which there is a gap between excitation capacitive probes and radiating patch. In Ref. **wong2004design**, a microstrip patch antenna is excited using two L-shaped capacitive probes. In the presented design in Ref. **wong2004design**,

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Fig. 3: Probe-fed microstrip patch antenna; (a) Square patch, (b) Circular patch.

input isolation of 20 dB is reported. Different configurations such as hook-shaped and T-shaped meandering probes have been proposed to improve the horizontal to vertical ports isolation. Also, it is shown that surrounding the antenna with metallic walls, will result in a better isolation. An isolation level of better than 30 dB by using metallic walls is reported in **mishra2014review**.

The aperture-coupled patch antenna was first introduced by Pozar **pozaraperurecoupled**. This type of patch antenna has been studied and developed into different dual-polarized designs. Fig. 5 shows several configurations which have been implemented and discussed in the literature. A dual-polarized aperture coupled patch antenna can be realized through a centered crossed-slots or two separated orthogonal slots. In the crossed-slot

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Fig. 4: A dual-polarized probe-fed microstrip antenna; (a) 3-d configuration, (b) L-shaped probes, (c) Hook shaped probe, (d) Meandering probe **mishra2014review**.

design in order to avoid overlapping between two orthogonal feed lines, a double layer substrate or an air bridge is required unless the non-overlapping feed lines method is utilized.

Dual-polarized aperture-coupled patch antennas with two separate slots and two non-overlapping feed lines etched on the same side of a substrate can be used when high-isolation is required. The back lobe level in the aperture-coupled patch antennas can be enhanced by using a ground plane below the feed lines.

The impedance bandwidth of microstrip patch antenna is typically %3. Different bandwidth enhancement methods have been proposed, in the open

Chapters/AntOveView/fig5.pdf

Fig. 5: Some configurations of dual-polarized slot-coupled patch antennas **caso2011dual**.

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Fig. 6: Microstrip patch antenna excited using balanced feed method.

literature. Using thick dielectric material and implementing stacked patch configuration are among well-known bandwidth enhancement methods. In the multilayer configuration, a parasitic square patch with smaller or larger dimensions is placed on top of the radiating square patch. While using the thick dielectric material for increasing the bandwidth, it should be noted that this may result in a distorted radiation pattern. This is because increasing the substrate thickness will result in excitation of stronger higher order modes. To cancel higher order modes, microstrip patch antennas can be excited through two probes, placed on opposite locations and excited with 180° phase difference. Fig. 6 shows the balanced feed or differential feed method proposed by Chiba in 1982 **Chibadiff**. Balanced feed method will significantly reduce the cross-polarization level of the antenna and in dual-polarization configuration, and a very high input isolation between horizontal and vertical polarization.

In the hybrid feed technique, different excitation methods are combined. With an appropriate design, the hybrid feed method could result in a compact design, low cross-polarization radiation pattern and high input isolation. Compared to the dual-polarized differential feed design, the hybrid feed design requires less space for feed lines, which results in a more compact design **saeidi2017hybrid**. Also, the hybrid feed design provides a more symmetric feature which will improve the isolation between the horizontal and vertical ports. The geometry of a dual-polarized hybrid-fed microstrip patch antenna is shown in Fig. 7. In this design, one port is excited through two in-phase aperture-coupled feeds, and the other port is excited using two out-of-phase gap-coupled probe feeds **chiou2002broad**. In this design the cross-polarization level of lower than -20 dB and input isolation of -40 dB

Chapters/AntOveView/fig7.pdf

Fig. 7: Geometry of a broad-band dual-polarized square patch antenna fed by two in-phase aperture-coupled feeds (port 1) and two out-of-phase gap-coupled probe feeds (port 2) **chiou2002broad**.

were realized. In **wong2002broadband**, a dual-polarized patch antenna is fed by an aperture coupled feed and two capacitively coupled feeds of a 180° phase shift. In this design, the input isolation of better than 32 dB and cross-polarization level of -14.4 dB were reported.

0.3 Phased Array Radar

One way to increase the antenna gain and achieve more directive radiation pattern is to increase the dimension of the single element. One way of increasing the antenna gain, without increasing the single elements size is to arrange single elements beside each other in a geometrical and electrical configuration. The new antenna which is made of multiple single elements is called an array antenna or antenna array.

IEEE standard definition of the term for antenna array (array) is as follows: "array antenna; antenna array. An antenna comprised of a number of identical radiating elements in a regular arrangement and excited to obtain a prescribed radiation pattern.

NOTES: (1) The regular arrangements possible include ones in which the elements can be made congruent by simple translation or rotation. (2) This term is sometimes applied to cases where the elements are not identical or arranged in a regular fashion. For those cases qualifiers shall be added to distinguish from the usage implied in this definition. For example, if the elements are randomly located one may use the term random array antenna." Phased array antennas are made of several fixed elements, in which each element is being fed by variable amplitudes and phases to form the beam and scan the beam to specified angles.

A conformal array antenna is an antenna which its shape has been determined by another object. This could be a car, a building, airplane or any other object. The purpose of designing conformal antenna arrays could be the integration of the antenna with other objects to be less disrupting or less visible. In some other applications, the conformal geometry will decrease the backscatter radiation when the antenna is illuminated by another radar antenna.

The IEEE Standard Definition of Terms for Antennas (IEEE Std 145-1993) gives the following definition:

Antenna [conformal array]. An antenna [an array] that conforms to a surface whose shape is determined by considerations other than electromagnetic; for example, aerodynamic or hydrodynamic.

Conformal array. See: conformal antenna.

By this definition planar antenna is also a type of conformal antenna when the shape of the array is determined with reasons other than electromagnetic considerations. However in practice, usually the spherical, cylindrical and some other shapes are considered as conformal array geometries.

Cylindrical array antennas without shape being dictated by non-electromagnet reasons are usually considered conformal arrays. In cylindrical polarimetric phased array radar antenna, the shape is determined by electromagnetic requirements such as low cross-polarization, matched horizontal and vertical and scan invariant radiation patterns. A cylindrical array antenna has a potential of 360° coverage either with a narrow beam that can steer over 360° or an omnidirectional beam, multiple beams.

As mentioned before, in a phased array the fixed element elements can be fed by variable amplitudes and phases to form and steer the antenna array radiation pattern. Depending on the array antenna configuration the amplitude and phase of excitation of each element can be calculated. For linear and planar antennas, the array radiation pattern can be estimated based on the element pattern and the array factor. The array antenna IEEE standard definition for array factor is as follows:

"**Array Factor.** The radiation pattern of an array antenna when each array element is considered to radiate isotropically. NOTE: When the radiation patterns of individual array elements are identical, and the array elements are congruent under translation, then the product of the array factor and the element radiation pattern gives the radiation pattern of the entire array."

Circular and cylindrical arrays possess an advantage of the symmetrical radiation pattern in azimuth, which makes the circular and cylindrical array configurations very interesting for radar applications. However, calculating the antenna radiation pattern is more complicated compared to linear and planar array antennas since the element radiation pattern also depends on the element location. Therefor, in circular and cylindrical array antenna coherent addition method is being used for calculating the array radiation pattern. Multifaceted array antenna geometry is the combination of planar and cylindrical configurations. The analysis of the multifaceted array antenna is more complicated than cylindrical array antennas. The primary advantage of multifaceted arrays compared to the cylindrical arrays is lower fabrication cost.

0.4 Multifunction Phased Array Radar

The beam agility, higher angular resolution **zhang2015hybrid** and faster data update of phased array technology compared to a conventional mechanically scanned antenna can enable a single phased array radar to perform multiple tasks at the same time **heimmer2008multi**. Currently, there are four radar networks: (1) National Weather Surveillance Radar (WSR-88D or NEXRAD); (2) Terminal Doppler Weather Radar (TDWR); (3) Airport Surveillance Radar (ASR); and (4) Air Route Surveillance Radar (ARSR) which are serving the United States on their own missions separately. There are issues such as overlap of coverage and functionality and difficulty in data sharing among these radar networks. To avoid these issues and advance air and weather surveillance capability, a single Multi-Function Phased Array Radar (MPAR) network is being proposed and developed by a joint effort of the National Oceanic and Atmospheric Administration's (NOAA's) and the Federal Aviation Administration (FAA) **stailey2016multifunction-zhang2016weather**. Also, since WSR-88D has been updated with the dual-polarization capability, the future MPAR should also have this capability **golbon2016detection**. Using a single radar for long-range, short-range, and weather applications can also result in vacating the 1300-1350 MHz spectrum for commercial use.

While Polarimetric Phased Array Radars (PPAR) have been developed for military and space applications **jordan1995sir**, PPAR cannot be used for MPAR directly because of their limited scan angles and aperture sizes. Planar Polarimetric Phased-Array Radar (PPPAR) and Cylindrical Polarimetric Phased-Array Radar (CPPAR) are being considered as the next generation of radars for MPAR **zhang2011polarimetric**, **karimkashi2013dual**. PPPAR, however, has fundamental shortcomings in beam characteristics changing and polarization coupling depending on beam direction, and limitations in making high-quality weather measurements. It is crucial to design and develop a high-performance array antenna to achieve the goals of MPAR **doviakmemorandum**, **lei2013bias**.

MPAR is required to operate according to the Manual of Regulations and Procedures for Radio Frequency Management (47 Code of Federal Regulations (CFR) Part 300) and FAA Order 6050.19. Regarding operational bandwidth, when replacing ASR and TDWR, MPAR is required to operate in the 2.7 - 2.9 GHz band, one which is allocated for aeronautical radio navigation. However, when replacing the WSR-88D and the ARSR radars (i.e., so-called Long Range Radars; LRRs), the MPAR must operate in 2.7-3.0 GHz. For the National Weather Service (NWS) application, elevation scan angles less than 20° MPAR must provide differential reflectivity (Z_{DR}) estimates with a bias no more than 0.1 for the $Z_{DR} \leq 1$ dB **FAAreport**. The primary objective of this dissertation is meeting the cross-polarization requirement of MPAR. For the MPAR applications, the cross-polarization level and horizontal and vertical ports isolation should be close to current WSR-88D measured characteristics. Based on measured and theoretically calculated copolarization and cross-polarization radiation patterns for the WSR-88D, the cross-polarization field has a null along the co-polarization beam **lei2015comparison**. However, if cross-polarization radiation has a lobe coaxial with the co-polarization beam, the requirement that Z_{DR} bias should be less than 0.1 dB, requires the cross-polarization peak to be more than 45 dB below the copolarization peak **zrnic2010bias**. This level of cross-polarization can be relaxed if phase coding is used **ivic2016evaluation**. If a cross-polarization lobe is coaxial with the copolarization beam, the largest relaxation in the peak level of a coaxial cross-polarization lobe is attained if the two polarizations are either in or out of phase with each other. In this case, the peak level of the cross-polarization radiation is relaxed to about 26 dB below the copolarization peak **zrnic2012Issues**.

0.5 Outline of the Dissertation

This dissertation is devoted to design, fabrication, and characterization of phased array antennas with a low cross-polarization level and high input isolation between horizontal and vertical polarizations. The primary goal is to investigate the capability of microstrip patch antennas for MPAR applications. Therefore, all the designed and presented antennas in this dissertation are based on microstrip patch antennas.

In chapter 2, three different low cross-polarization, high-isolation dual linear polarized microstrip patch antennas are designed for MPAR application. In the first design, a dual-polarized microstrip patch antenna is excited through the aperture coupling method. Although dual-polarized aperture-coupled patch antennas with two non-overlapping feed lines laid on a single side of a laminate have been implemented for several applications, an array of very high isolation and low cross-polarization that meets MPAR requirements has not been reported. In the second design, the hybrid feed technique is implemented. In the presented hybrid fed patch antenna, the horizontal polarization is excited through the differential probe feed method, and the vertical polarization is excited through an H-shaped aperture in the middle of the ground plane. In the third presented patch antenna, the horizontal polarization is excited through two 180° out of phase apertures, and vertical polarization is excited by an aperture in the middle of the ground plane.

In chapter 3, the challenges and limitations of using cross-polarization suppression methods for dual-linear polarization antenna arrays are presented. A simple probe-fed patch antenna and a high-performance, high isolation, low cross-polarization dual-polarized patch antenna are used for this study. The image feed method is used for improving the cross-polarization level and increasing the geometrical symmetry of the large array antenna. It is shown that decomposing the antenna radiation pattern to its even and odd components for calculating 2×2-element subarray radiation pattern has fundamental limitations and none of the four different 2×2-element subarray configurations will entirely suppress the sidelobe issue of configured arrays. The accuracy of using embedded element pattern for calculating the radiation pattern of the large array with identical subarrays is studied and an accurate procedure for predicting array antenna radiation pattern is proposed. The appearance of undesired sidelobes has been studied, and optimal design for the large array of 2×2-element subarrays with image configuration is presented to avoid the sidelobes.

In chapter 4, the performance of the designed single elements in chapter 2 are characterized while these designs are implemented in an array. To improve the cross-polarization level, the 2×2-element subarrays of the proposed single elements are designed, fabricated and tested. To characterize the radiation pattern of the designed subarrays, the planar arrays of the presented subarrays, are fabricated, and the radiation pattern of the antenna arrays at broadside and various scan angles are provided and discussed.

In chapter 5, a method of beam matching between two linear polarized radiation patterns of a dual-polarized frequency scanning antenna for CPPAR is proposed, implemented, and tested. A meticulous phase match process between the outputs of both individual cells and the whole corresponding horizontal and vertical feed lines is carried out. To verify the simulation results and to take the coupling effect into account, the radiation patterns of an isolated column, as well as those of three columns, are measured. In agreement with the design and simulation results, horizontal and vertical polarization beams with a pointing angle mismatch of less than $\pm 0.2°$ within the resonant frequency bandwidth of 2.75-2.95 GHz are achieved.

Chapter 6 concludes the dissertation by providing a summary of the work.