Aperture-Coupled Microstrip Patch Antenna Design using FEM Simulation Technique

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Abstract –**The recent developments in microwave systems, put high requirements to antenna arrays for RFID and radar applications, in terms of pattern shape and side lobe specs. The presented paper discusses an inexpensive approach for amplitude distribution control of aperture-coupled microstrip patch antenna, as a building block of more complex array systems.**

Keywords – **Aperture-coupled; rotation; microstrip; patch; antenna; open-ended; stub.**

I. INTRODUCTION

Microstrip antennas find great usage in modern telecommunication, detection and ranging systems (i.e. radar systems). The advantages of this antenna type are many for both commercial and warfare applications - low profile, conformable to planar and nonplanar surfaces, simple and inexpensive to manufacture using modern printed-circuit technology, mechanically robust when mounted on rigid surfaces. Compatibility with RF designs utilizing surface mounted technology makes them a preferred choice for highly integrated, cost-optimized devices like the ones modern autonomous driving and broadband cellular services demand.

Some applications of the microstrip patch antenna require the feed line to be separated from the radiating surface of the antenna in order to achieve gain, bandwidth, element-to-element separation, and other design targets. One such approach is feeding the element with an aperture-coupled transmission line. When implemented on a printed circuit board, a microstrip feed line and any required surface mount components can be situated on the opposing plane of the board, thus reducing the total design outline.

In order to understand the microstrip antenna's performance and to streamline the antenna design process, several numerical analysis techniques have been developed and concerted to computer-aided design (CAD) and electromagnetic simulation (EM) tools. This approach offers optimal balance between minimized simulation completion-time and maximized correlation between simulated results and real-world measured data.

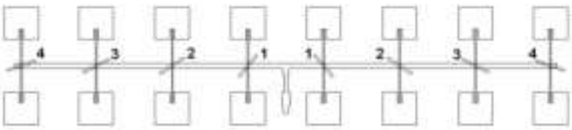

Fig. 1 Aperture-Coupled Series fed Array

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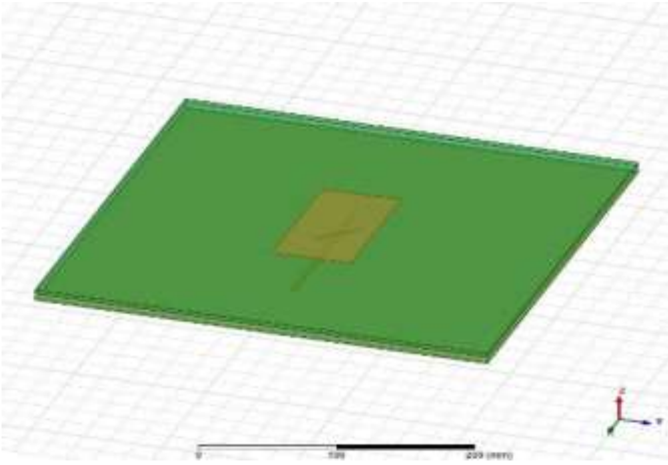

Fig. 2 Aperture-Coupled Microstrip Patch Antenna 3D Model

In order to achieve control over the amplitude distribution and thus, control the shape of the main beam, several design approaches are developed to date. One of the most promising and low-cost is proposed by [1]. The array consists of several paired radiators, whose excitation is controlled with inclined slot, electrically coupled with common transmission line *(Fig. 1)*. The present paper analyses the performance of direct control of the excitation of a single printed radiator, which gives more array design flexibility and provides it as a building block of more complex antenna arrays.

II. APERTURE-COUPLED MICROSTRIP PATCH ANTENNA MODEL

The aperture-coupled microstrip patch antenna (

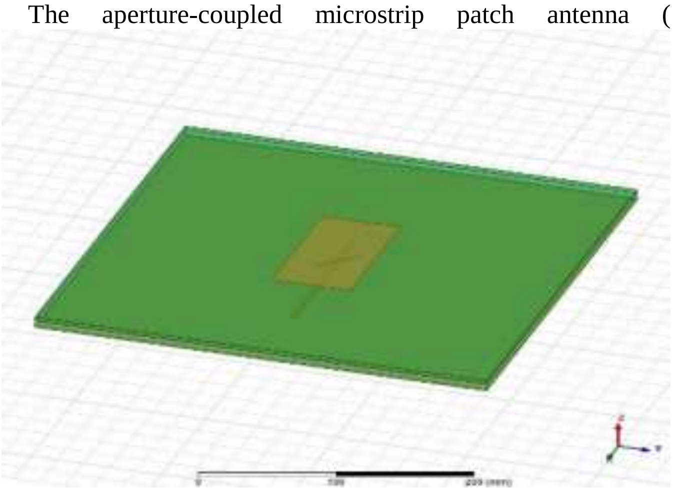

Fig.) is a multi-planar structure that avoids a direct connection between the radiating element and the feed line. The proposed model consists of a patch element etched in copper on the outward-facing layer of a substrate, an air cavity, a copper ground plane with the coupling slot etched into it, a second dielectric layer and a microstrip feed line etched in copper on the opposing outwards-facing layer. With the radiating surface and the feed line placed on the opposing sides of the printed circuit board the electromagnetic coupling is achieved through the aperture in the ground plane situated in between these two planar structures. The orientation, the position and particularly the length of the aperture directly influence the amount of energy coupled to the antenna and the back radiation as well. Maximum coupling is achieved when the aperture is centered with respect to the microstrip patch element. Thus, the shape, size and position of both the radiating element and the coupling slot can be varied to achieve the target impedance matching and directivity [2]. This makes such antenna elements particularly desirable for size-constrained phased arrays.

In a series-fed design, the slot's angle of rotation in respect to the feeding line (*Fig.* 3*4*) can be used to implement side-lobe-reducing amplitude tapering. Such approach has the advantage of all the patch elements having the exact same geometry, making the inter-element coupling easier to estimate and account for early on in the design process.

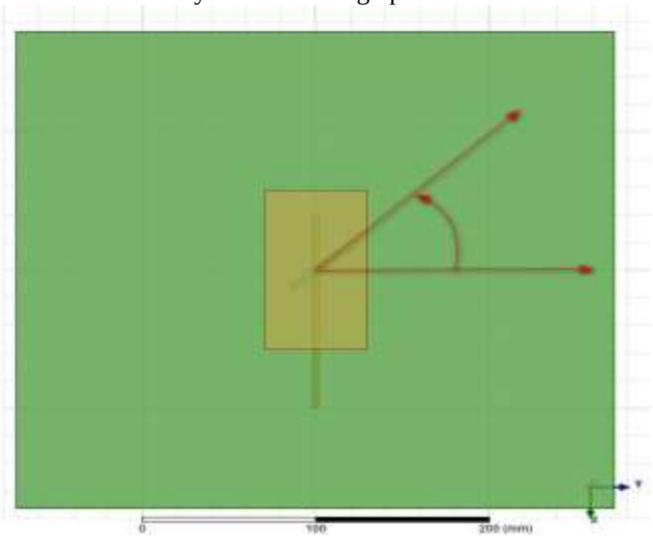

Fig. 3 Top view of proposed aperture-coupled microstrip antenna element, showing the slot rotated at an angle in respect to the feeding line

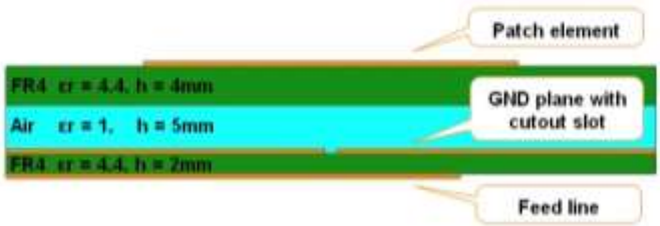

Fig. 4 Proposed aperture-coupled microstrip antenna stack-up

Great advantage of this multi-layer structure is that it is implemented over two independent dielectric layers as shown on

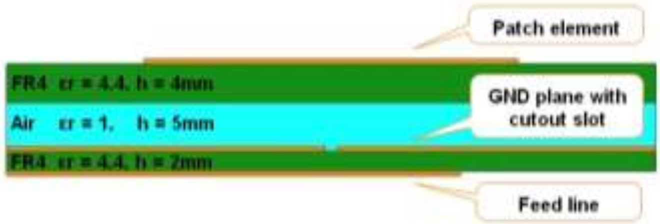

Fig. 4. The substrate for the radiating element and the substrate for the feed line can be optimized separately from one-another in order to achieve lower unwanted back-radiation and higher boresight realized gain in a single design. The selection of a thick low-permittivity substrate or an air-filled cavity is necessary to obtain a broadband microstrip antenna with high gain.

Developing an understanding of the concept of bandwidth is fundamental for any type of antenna analysis because this parameter directly relates to how an antenna is designed and how the antenna can perform. It can be defined as the frequency range over which the antenna satisfies the design requirements. The bandwidth of an antenna is dependent not only on the radiating element's capability to couple RF energy into free space but also on the quality of the impedance matching between the antenna, the source, and the transmission line. As the operating frequency moves outside of the antenna's bandwidth, the performance suffers because of an impedance mismatch. As the operating frequency changes, the imaginary component of the impedances will change as well. As the impedances change, they can become mismatched at certain frequencies and thus can affect the antenna's performance. For this reason, impedance matching must be considered so that the antenna can operate over the desired frequency range [3].

Furthermore, the center frequency of the aperture-coupled patch is mainly controlled by the relative permittivity of the patch substrate and the length of the patch. The bandwidth increases with the thickness of the substrate, but the coupling decreases. So, the substrate thickness should be large enough to fulfill the bandwidth requirements, yet small enough to realize a proper coupling [4].

In contrast to the bandwidth, the efficiency of the patch antenna decreases when increasing the substrate thickness and the relative permittivity of the material [3].

The proposed design uses a Wave-port to feed a 50-ohm microstrip line situated on the bottom layer of the modeled printed-circuit board stack. The purpose of the feed line is to carry energy from the source to the radiating element through the coupling slot. To achieve stable impedance matching of the antenna and good coupling factor an open-ended microstrip stub is used to terminate the transmission line after the coupling point. Using optimization techniques, the stub's length was determined to be a bit less than the quarter-wavelength of the targeted center frequency of 868 MHz ISM band. When running a FEM simulation of the model it is useful to plot the current distribution on the feed line in order to find the optimum stub length. Using the same method, largest coupling factor was estimated when the patch is centered over the aperture.

The ground plane on the adjacent layer has a cutout acting as a coupling slot between the feed line and the area towards the top of the stack. This aperture adds parasitic inductance to the feed line which shifts down the design's resonant frequency.

Enlarging it results in better coupling at the cost of increasing the parasitic inductance and so unmatching the design from the nominal input impedance. Increasing the coupling slot's area up to a certain design-dependent point increases the realized gain, and beyond that point impedance mismatching leads to sharp decrease of the gain at the intended frequency. It is still debatable what the optimum length of the coupling slot should be - increasing it too much will lead to secondary resonance of the antenna. In such state the bandwidth increases, but so does the back-lobe radiation. The slot length was determined to be somewhat shorter than the quarter-wave of the center frequency inside the transmission line's dielectric layer. The width of the aperture is also varying greatly in the literature with values around 1/10-th of the slot's length being coined the most [2]. After evaluating the width using FEM simulation methods it was observed that slightly wider aperture results in better coupling and lower back-lobe realized gain of the design.

III. Simulation Results

Electromagnetic simulations have been performed with the use of Ansys' High Frequency Structure Simulator (abbreviated HFSS^{TM} for short) software. HFSS uses a numerical technique called the Finite Element Method (FEM). This is a procedure where a structure is subdivided into many smaller subsections called finite elements. The finite elements used by HFSS are tetrahedra, and the entire collection of tetrahedra is called a mesh. A solution is found for the fields within the finite elements, and these fields are interrelated so that Maxwell's equations are satisfied across inter-element boundaries. Yielding a field solution for the entire, original, structure. Once the field solution has been found, the generalized S-matrix solution is determined [5].

The aperture-coupled patch antenna microstrip feed line, substrates, ground plane slot dimensions, and patch dimensions are varied in HFSS to determine their effects on antenna performance. The antenna design's optimal performance was obtained and afterwards coupling slot was rotated at an angle in respect to the feeding line to observe its effect on the overall performance (*Figure 2).*

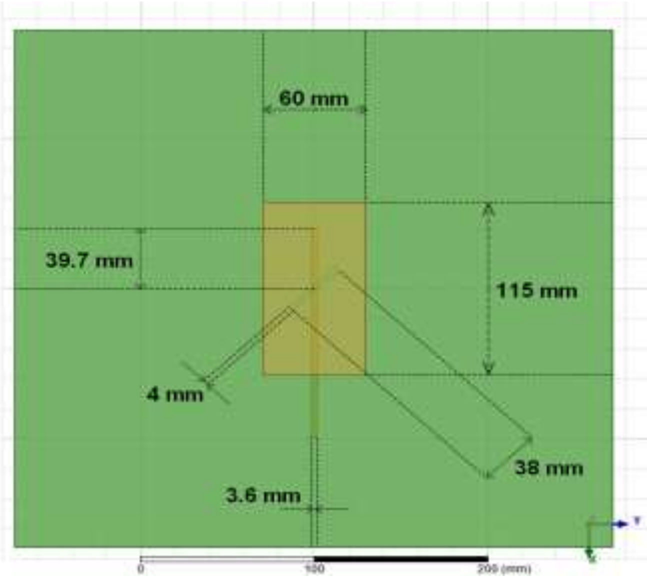

Figure 2 Proposed aperture-coupled microstrip antenna element dimensions

The operating frequency, reflection coefficient, bandwidth, polarization ratio, and realized gain are observed for each variation. The frequency where the minimum reflection coefficient value occurs defines the operating frequency. The bandwidth is the frequency range over which reflection coefficient is less than -10dB. On *Fig. 3* is shown that the antenna's with coupling slot perpendicular to the feed line central frequency occurs at 868MHz with 23 MHz bandwidth.

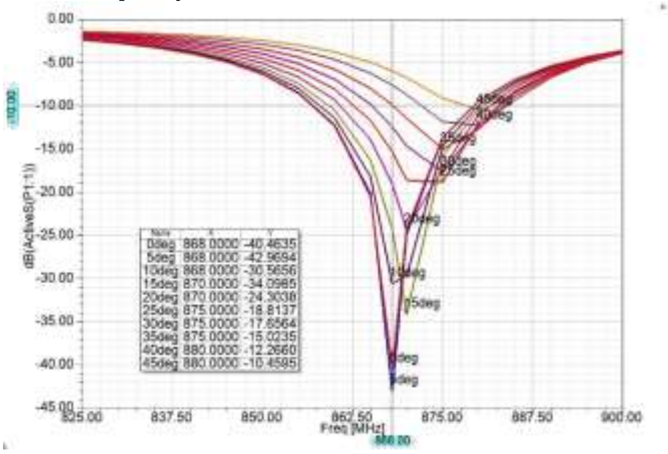

Fig. 3 Reflection coefficient in relation to various Slot Rotation Angles

Great function of the Smith chart is the ability to determine how good the impedance matching is. The results for the reflection coefficients with coupling slot rotated at certain angle in respect to the feed line plotted in the Smith Chart are presented in *Fig. 4*.

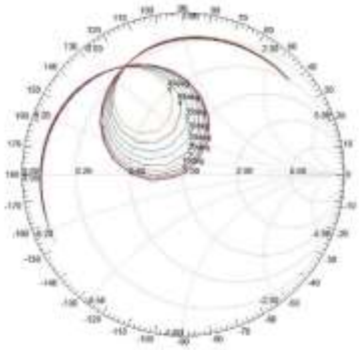

Fig. 4 Reflection coefficient in relation to various Slot Rotation Angles

The polarization ratio is the co-pol to cross-pol ratio in the far field. Aperture-coupled microstrip patch antennas have polarization ratios 10dB greater than other microstrip patch antenna configurations [2].

When the coupling slot is perpendicular to the feed line, the co-pol realized gain is 7.39dB (*Fig. 5*) and the cross-pol realized gain is -50.67dB (*Fig. 6*). This yields a polarization ratio (also known as cross-pol separation) of 58.06dB.

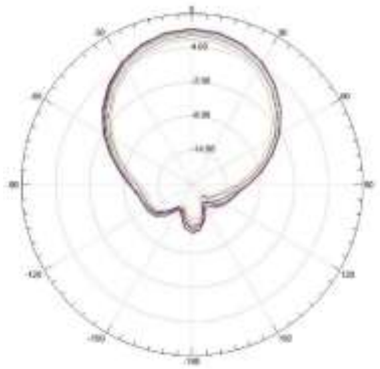

Fig. 5 Co-pol Radiation Pattern in relation to various Slot Rotation Angles

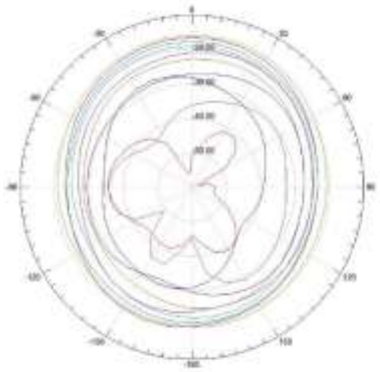

Fig. 6 Cross-pol Radiation Pattern in relation to various Slot Rotation Angles

The total realized gain from all polarizations is determined at the center frequency of the antenna's intended operating range. On *Fig. 7* realized gain is plotted in function of coupling slot angle of rotation. By rotating the coupling slot, it is possible to achieve the appropriate amplitude tapering.

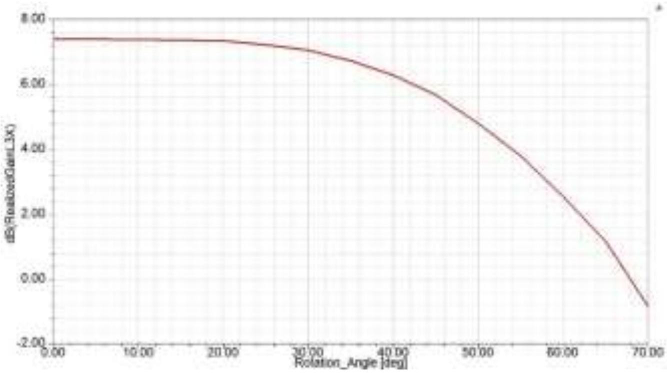

Fig. 7 Realized Gain at Boresight to Slot Rotation Angle

The back-radiating lobe is due to microstrip feed line radiation caused by impedance mismatch. After evaluating the coupling slot's rotation angle as a design parameter (*Fig. 8*), the authors came to the conclusion that this variation does not have a negative impact on the back-side radiation. This is due to the transmission line being terminated with an open-ended stub. This structure shorts the uncoupled RF energy.

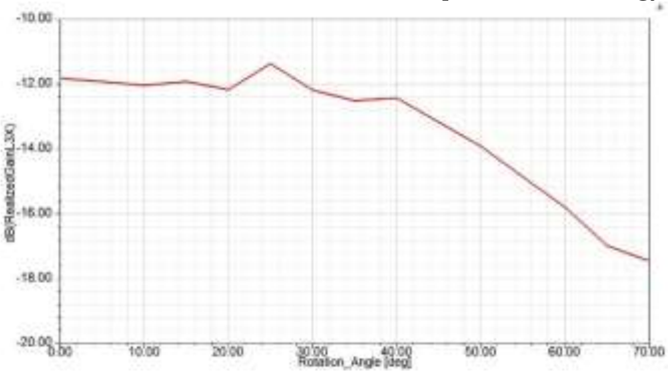

Fig. 8 Back-side Radiation to Slot Rotation Angle

IV. CONCLUSION

The relation between the rotation angle of the coupling slot and the antenna's impedance matching makes the patch element particularly useful for series-fed microstrip patch phased arrays.

The rotation angle of the coupling slot has particularly useful effect of reducing the backside radiation at a predictable rate.

The proposed design exhibits a linear degradation of the realized gain when rotating the coupling slot, with a strong roll-off from around 70deg. This is due to the change of the coupled mode of the feed line.

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