Aperture Coupled Patch Antenna Design Methods

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Abstract— **Microstrip patch antennas have been used extensively in applications requiring low-profile, mounting structure conforming, and low-cost wireless communications. Feed methods (antenna-transmission line interface) are critical for optimum performance. The aperture coupled technique exhibits reduced transmission line radiation and enhanced antenna radiation and co- to cross-pol performance relative to microstrip and probe fed configurations. Researchers have focused on analytical methods and design improvements without identifying parametric tradeoffs or design methods. Hence, this paper presents theoretically and parametrically identified critical antenna dimensions and performance effects, and a design procedure to convert desired performance requirements into operational prototypes.**

Keywords–Aperture coupled; antenna design; microstrip antenna.

I. Introduction

The aperture coupled microstrip patch antenna feed technique [1] was introduced in 1985 that includes electrically isolated microstrip transmission lines and patch conductors. These structures are electromagnetically coupled through a small aperture in the isolating ground plane (Fig. 1) [1]. Two common feed techniques for patch antennas are directly connected microstrip transmission lines and coaxial probes

A microstrip transmission line feed directly connects a microstrip line to the radiating patch. Source electromagnetic fields are concentrated between the microstrip line and ground plane to excite primarily guided waves as opposed to radiated or surface waves. Guided waves are dominant if the dielectric is electrically thin ($<\lambda/50$) and has a large permittivity relative to free space ($\varepsilon_r > 5$) [2]. At the radiating patch, it is desirable to decrease guided waves under the patch and increase radiated waves at the patch edges. This requires an electrically thick dielectric ($>\lambda/10$) substrate with a relatively low permittivity ($\varepsilon_r < 3$). Compromising between the two conflicting criteria results in surface waves, reduced radiation efficiency due to guided waves below the patch, and increased sidelobes levels and cross-polarization levels from spurious feed line radiation [2].

A probe fed microstrip patch antenna is excited by a coaxial line center conductor; the outer coaxial conductor is electrically connected to the ground plane. For this geometry, substrate thickness and permittivity are optimized for radiation efficiency. However, the probe center conductor underneath the patch causes field distortion due to the introduction of an undesired reactance at the antenna input and a relatively large probe self reactance [2], [3].

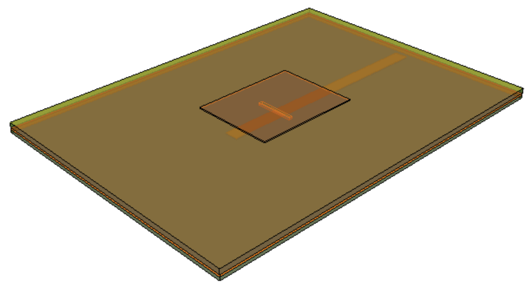

Figure 1. Aperture Coupled Microstrip Patch Antenna, Transparent Structure: Bottom Layer: Microstrip, Center: Ground Plane & Slot, Top: Patch

An aperture coupled antenna eliminates the direct electrical connection between the feed and radiating conductors by employing two dielectric substrates separated by a ground plane. This allows independent optimization of both the microstrip transmission line feed and radiating patch. Aperture coupled antennas are used in phased arrays due to phase shift and feed circuitry isolation from the patch antennas. However, the required multilayer structure increases fabrication complexity and cost [2].

II. Aperture Coupled Patch Antenna Model

The ground plane slot between the feed and antenna substrates can be modeled as an impedance transformer and parallel LC circuit (L_{ap} and C_{ap} in Fig. 2-1) in series with the microstrip feed line [2]. The N:1 impedance transformer represents patch antenna impedance effects coupled through the ground plane slot, while the LC circuit represents ground plane slot resonant behavior and patch edge fringing field effects. Fig. 2 shows an equivalent circuit model for the aperture coupled patch antenna.

Nominal antenna circuit model parameters are determined from equations (3.1) through (3.8) in [6]. The nominal antenna equivalent circuit model was created in ADS. Table 3-2 in [6]

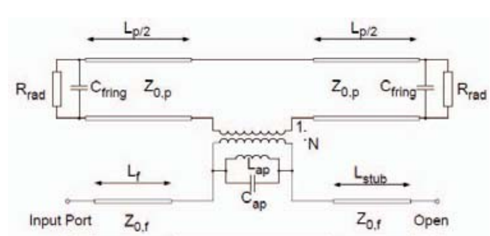

Figure 2. Equivalent Circuit, Aperture Coupled Patch Antenna [2]

contains nominal antenna parameter values for equations (3.1) through (3.8) in [6] at 2.3GHz. Lap and Cap are initially selected to satisfy equality in (3.8) in [6]. The impedance transformer turns ratio N is initially selected as the nominal patch width to slot length ratio (3cm/1.4cm). L_{ap}, C_{ap}, and N are adjusted in an ADS equivalent circuit model to match HFSS $VSWR_{in}$ vs. frequency results. Through ADS parametric adjustments, it is empirically determined that impedance transformer turns ratio N is inversely proportional to bandwidth and operating frequency, and directly proportional to minimum $VSWR_{in}$.

Fig. 3 shows $VSWR_{in}$ vs. frequency for the nominal HFSS antenna [1] and ADS2009 equivalent circuit model. Minimum $VSWR_{in}$ is 1.858 at 2.279GHz and 1.879 at 2.280GHz for the nominal HFSS antenna model [6] and equivalent circuit model, respectively. The bandwidth is 20MHz and 19MHz (0.88% and 0.83% of operating frequency) for the nominal HFSS antenna model and equivalent circuit model.

III. Parametric Study

Aperture coupled patch antennas involve performance-critical parameters including substrate thickness, substrate dielectric constant, microstrip feed line, ground plane slot, and patch dimensions and relative locations. A parametric study was completed to determine performance effects of critical parameters to develop a design procedure [6]. The operating frequency, VSWR, percent bandwidth, polarization ratio, and broadside gain were observed for each configuration. The operating frequency f_o is defined at the minimum $VSWR_{in}$ over the test bandwidth; the $\Delta f/f_o$ ratio, where Δf is the "$VSWR_{in}$ less than 2" range. The polarization ratio is the E-field co-pol (θ-polarized) to cross-pol (φ-polarized) ratio in the far field normal to the patch (broadside). The total broadside gain from all polarizations was determined at the antenna operating frequency. All dimensions (in wavelengths) were determined with ADS2009 LineCalc at 2.3GHz for 63 mil thick RT Duroid; dielectric constant 2.2, loss tangent 0.0009.

Fig. 4 identifies the ground plane (orange) and ground plane slot (yellow). Slot Width and Length Offsets define distances between the slot center and a point directly below the radiating patch center (z-axis). Both parameters are

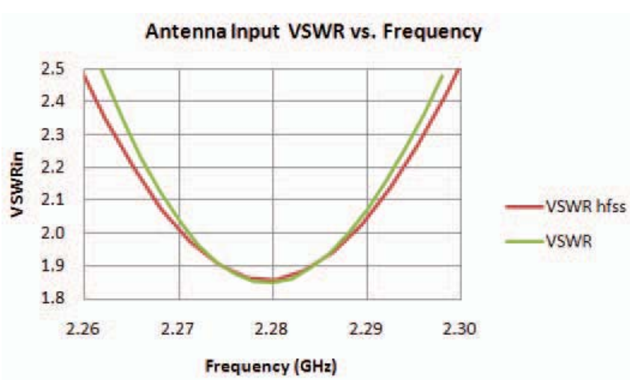

Figure 3. HFSS Model and Equivalent Circuit Model: $VSWR_{in}$ vs. Frequency

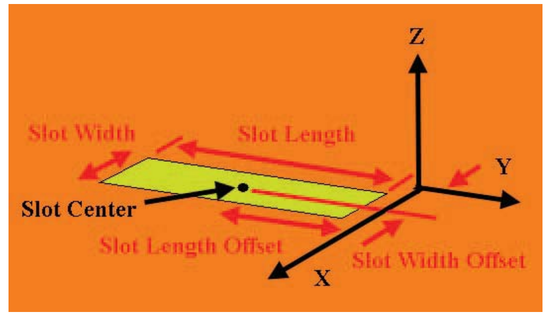

Figure 4. Slot Dimensions and Variables

nominally zero. Nominal slot dimensions are 0.148λ by 0.016λ (Slot Length and Width) equivalent to 551.2mils by 61.0mils [1].

Parametric variations in the above four dimensions identifies optimum slot dimensions of 0.141λ by 0.019λ (Slot Length and Width) at 2.3GHz. Fig. 5 shows the four patch variables: Patch Width and Length Offsets, and Patch Width and Length. Offsets are measured relative to the coordinate system origin (see Fig. 5) to the patch center. The coordinate system origin is at the patch center is the offsets are zero.

Patch Length is nominally 1.575 inches (0.422λ). Fig. 6 shows that operating frequency decreases with increasing Patch Length. Resonant frequency approximates a constant slope function of Patch Length between 0.78 and 2.50 inches. The average slope in this range is -1.295 kHz/inch; hence, varying Patch Length adjusts the operating frequency.

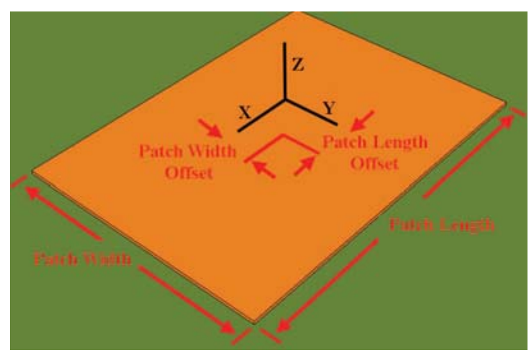

Figure 5. Patch Variables

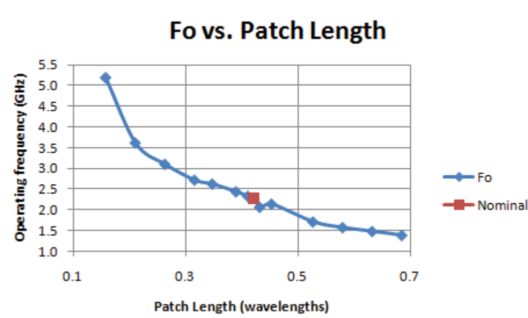

Figure 6. Operating Frequency vs. Patch Length

The antenna model is shown below in Fig. 7. The feed strip is on the bottom-most layer (thin, long rectangle in Fig. 7). It is excited via an edge-connected SMA at the end labeled “FEED POINT,” includes an open termination at the end labeled “OPEN TERMINATION,” and is electrically isolated from other layers by the ground plane.

Fig. 8 indicates that feed width offset errors of approximately 20mils (0.005λ) decrease broadside gain by 4dB.

Four 2.4GHz aperture coupled antenna designs were created in HFSS [6]. Gerber files were created in ADS for each conductive layer. Figs. 4, 5, and 7 define the coordinate system and variables adjusted to optimize antenna performance.

IV. Design

The nominal HFSS antenna design found in [1] (2.3GHz, 63mil Duroid 5880 substrate) was modified to operate at 2.4GHz, which corresponds to wireless computer and ISM equipment communications. The substrates were modified to 59mil thick FR4 suspended above the ground plane by 45mil thick, 375mil wide adhesive (3M VHB (very high bond) 4950 acrylic tape [7]) placed at the ground plane edges, see Fig. 9.

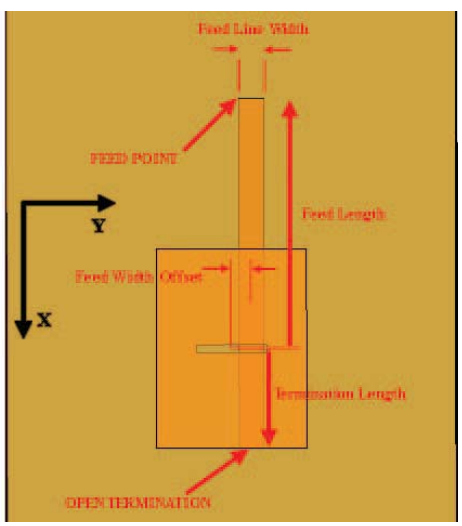

Figure 7. Feed Line Variables.

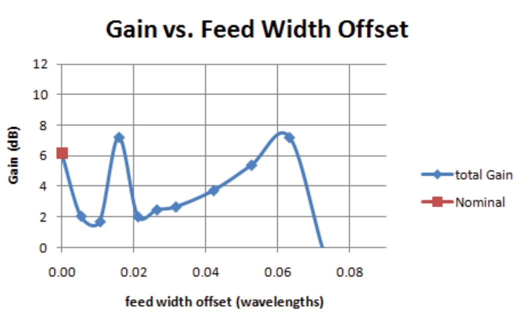

Figure 8. Gain vs. Feed Width Offset

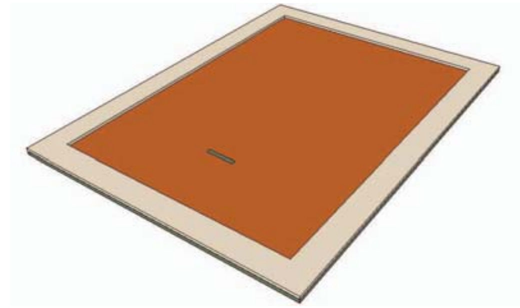

Figure 9. Double-sided FR4 Board with Ground Slot and Adhesive (drawn to scale)

Table I contains microstrip properties for the nominal [1] and fabricated [6] substrates. HFSS substrate models are defined by Table I parameter values. The substrates and ground plane lateral dimensions are 4.5” by 6”.

Patch, feed, and slot dimensions were adjusted to tune the operating frequency. It was determined that VSWRin is minimized and gain is maximized when only the patch and slot dimensions are used to tune the operating frequency. The operating frequency is adjusted by inversely scaling patch and slot dimensions (i.e.: halving slot and patch dimensions doubles the operating frequency). Table II shows dimensions (mils and dielectric wavelengths) for three aperture coupled patch antennas tuned to 2.4GHz.

The designs in [6] were created to apply the parametric study. Design 1 utilizes the patch and slot vs. frequency properties to tune operating frequency. Design 2 expands on Design 1 using patch width vs. input impedance properties to minimize $VSWR_{in}$. Design 3 expands on Design 1 also, but scales patch width and slot length by the same ratio to minimize $VSWR_{in}$. Table II shows the resulting dimensions for the three patch antennas designed using the parametric study results [6].

Table III contains HFSS simulation results for minimum VSWR, operating frequency (at minimum VSWR), bandwidth (GHz and percent), and antenna broadside polarization ratio and gain at f_o for Designs 1 through 3.

TABLE I. Microstrip Parameter Comparison

Parameter	Nominal [1]	Suspended FR4
Operating Frequency	2.3GHz	2.4GHz
Dielectric Constant	2.2	4.4 (FR4 only)
Eff. Dielectric Constant	1.891	1.882
Loss Tangent	0.0009	0.02 (FR4 only)
Wavelength in Dielectric	3,731.2mils	3,584.2mils
Substrate Height	63.0mils	59mils (+45mil air gap)
50Ω Line Width	194.0mils	385.8mils

TABLE II. PROTOTYPE DIMENSIONS

Dimension	Design 1 (mils, λ)		Design 2 (mils, λ)		Design 3 (mils, λ)	
Feed Length	1,412.6	0.528	1,412.6	0.528	1,412.6	0.528
Termination Length	565.0	0.211	565.0	0.211	565.0	0.211
Slot Width	59.8	0.022	59.6	0.022	59.8	0.022
Slot Length	542.1	0.202	539.8	0.206	555.1	0.207
Patch Length	1,548.8	0.578	1,542.5	0.576	1,548.8	0.578
Patch Width	1,161.4	0.434	939.4	0.351	1,122.0	0.419

TABLE III. THEORETICAL (HFSS) PERFORMANCE COMPARISON

Parameter	Design 1	Design 2	Design 3
Operating Frequency	2.398GHz	2.398GHz	2.396GHz
Bandwidth	0.062GHz	0.067GHz	0.065GHz
Percent Bandwidth	2.59%	2.79%	2.71%
$VSWR_{in}$ at f_o	1.340	1.069	1.181
Input Impedance @ f_o	40.1 + j8.74Ω	48.4 + j2.87Ω	45.1 + j6.16Ω
Broadside Pol Ratio @ f_o	41.7dB	51.63dB	50.08dB
Broadside Gain	5.291dB	4.970dB	5.427dB

V. CHARACTERIZATION

Designs 1 through 3 were fabricated and then characterized in the Cal Poly Anechoic Chamber. The operating frequency was determined using an HP8720C vector network analyzer. Table IV contains experimental results (Table III parameters) for Designs 1 through 3.

All three prototypes exhibit polarization ratios at least 13.6dB less than theoretical. Manufacturing tolerance studies indicate that this may be due to fabrication or material errors resulting in antenna substrate or adhesive tape height errors in slot width size or slot length offset [6].

All antennas have slot length offsets due to milling hole alignment errors on the double sided board. Designs 1 through 3 slot length offsets are 13mils, 23mils, and 17mils.

VI. DESIGN PROCEDURE

Four antennas were designed and tuned using the parametric study results from [6]. Three are discussed above. All four antennas exhibit greater than 2.42% percent bandwidth, less than 1.274 VSWRin, minimum 27.8dB broadside polarization ratio, minimum 5.585dB broadside gain, and are within 2.59% of the desired operating frequency. This indicates that the new design procedure (summarized below) can be used to design and tune aperture coupled microstrip antennas.

TABLE IV. EXPERIMENTAL RESULTS

Parameter	Design 1	Design 2	Design 3
Operating Frequency	2.442GHz	2.460GHz	2.423GHz
Bandwidth	0.059GHz	0.063GHz	0.063GHz
Percent Bandwidth	2.42%	2.56%	2.60%
$VSWR_{in}$ at f_o	1.080	1.137	1.137
Broadside Pol Ratio @ f_o	28.0dB	27.8dB	28.9dB
Broadside Gain @ f_o	6.009dB	5.836dB	5.585dB

Select a low-loss ($\tan\delta < 0.0001$), electrically thin feed substrate ($< \lambda/50$) with high dielectric constant ($\varepsilon_r > 5$) to maximize guided waves between feed line and ground plane [2].

Select a low-loss, electrically thick antenna substrate ($> \lambda/10$) with relatively low dielectric constant ($\varepsilon_r < 3$) to maximize radiated waves at the patch edges [2].

Set the feed line length to 0.739λ (feed dielectric wavelength) from feed point to open termination (see Fig. 7). Select feed line width for a 50Ω characteristic impedance. Position the ground slot and patch center above the feed line location 0.211λ (feed dielectric wavelength) from the open termination.

Set the ground plane slot length and width to 0.148λ and 0.016λ (antenna dielectric wavelength, see Fig. 4).

Set the patch length and width to 0.422λ and 0.317λ (wavelength in antenna dielectric, see Fig. 5)

Operating frequency is dependent on patch length, see Fig. 6. Adjust slot width and length, and patch width and length for desired operating frequency while maintaining the nominal slot width/length and patch width/length ratios from [1].

VII. ACKNOWLEDGMENTS

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