

Equivalent Circuit Modelling of Aperture-Coupled Microstrip Patch Antennas

G. N. Milford* and D. J. Cornforth

School of ITEE, UNSW@ADFA, Canberra, Australia

E-mail: g.milford@adfa.edu.au

Introduction

In this paper we present a new approach for identifying an equivalent circuit for the impedance of an aperture-coupled microstrip patch antenna (AC-MSPA). We then use this equivalent circuit to develop a simple design procedure for the AC-MSPA.

The AC-MSPA overcomes a number of the shortcomings of conventional probe-fed and edge-fed microstrip patch antennas (MSPA) [1]. These benefits are achieved at the cost of additional geometric complexity compared to the conventional MSPA. The general availability of CAD tools capable of relatively fast and accurate full-wave analysis of such structures enables a user to design an AC-MSPA using a ‘cut-and-try’ approach through repeated simulations. A disadvantage however of this approach is that it can be difficult for the user to gain insight into the underlying electromagnetic behaviour, and arriving at an optimum design cannot be guaranteed.

An equivalent circuit that accurately models an antenna’s input impedance as a function of frequency provides a mechanism to gain insight into the antenna’s electromagnetic behaviour [2]. Equivalent circuits for the AC-MSPA input impedance have been progressively developed over time [3], [4]. These circuits are reasonably complicated, consisting of a combination of lumped element components, ideal transformers and transmission line segments to represent the electromagnetic behaviour of the resonating patch and coupling slot. In this work we propose a simpler six component lumped element equivalent circuit for a square patch AC-MSPA, and apply the insight gained from this equivalent circuit to AC-MSPA design.

Characterisation and Modeling of the AC-MSPA

From a circuit viewpoint the coupling slot and patch structure can be modelled as an impedance Z_A inserted in series with the feedline at the centre of the coupling slot [5], as illustrated in Figure 1(a). Numerical values for the frequency response $Z_A(\omega)$ were obtained using CST’s MicrowaveWave Studio [6] using a modified AC-MSPA structure where the open-circuit stub was continued across the substrate to a second port. This 2-Port structure was preferred over the standard 1-Port AC-MSPA structure since we can exploit the symmetry of a centrally located slot to simplify de-embedding of the feedline from the simulated 2-Port S-parameter data to obtain Z_A . Simulated data were generated for the following range of geometry parameters: square patchsize $40 \leq PS \leq 80$ mm, coupling slot length $40 \leq SL \leq 100$ mm and patch substrate height $2 \leq HB \leq 12$ mm (although the slot width was also varied, it was subsequently determined that its variation had negligible effect on the data modeling). The patch and feed substrates used $\epsilon_r = 1$ and 3.38 respectively, the ground-plane and feed substrate size was 120 mm by 120 mm, and the feed substrate

height and feed-line width were 0.020 inch and 1.14 mm respectively. The patch was centered over the slot, which in turn was centered over the feedline.

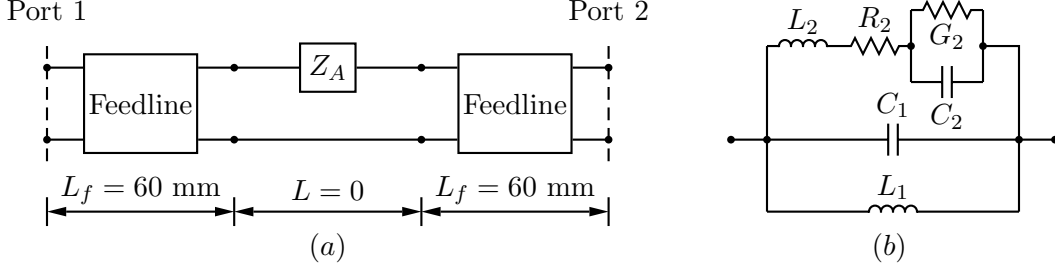


Figure 1: (a) network equivalent circuit for the 2-Port structure for characterising the AC-MSPA impedance $Z_A(\omega)$; (b) lumped element equivalent circuit for $Z_A(\omega)$.

The $Z_A(\omega)$ frequency response data contains the combined effects of electromagnetic coupling and the patch resonator behaviours. The equivalent circuit of Figure 1(b) provides a way of isolating the patch resonator behaviour (radiation) from the reactance associated with the resonator coupling to the feedline (coupling). Here we use a two-step process of arriving at an accurate equivalent circuit. Firstly, *VectFit* [7] is used to find a rational function approximation $Z_A(s)$ of $Z_A(\omega)$. Experimentation has found that only three poles are required to produce a reasonably accurate partial fraction expansion for $1/Z_A(s)$ over a frequency range covering the fundamental resonance of the AC-MSPA. The result is the six term lumped element equivalent circuit of Figure 1(b). Secondly, we further improve accuracy by optimising these component values to minimise the error between the reconstructed $Z_A(\omega)$ response from the circuit in Figure 1(b) and the original $Z_A(\omega)$ simulation data.

It is reasonable [3] to associate the four components L_2 , R_2 , C_2 and G_2 with the patch resonator, with L_1 and C_1 absorbing the remainder of the coupling reactance. The resonant frequency ω_o of the patch is defined as $\text{imag}(Z_p(\omega_o)) = 0$, where Z_p is the impedance of the L_2 , R_2 , C_2 , G_2 branch. Analysis of Figure 1(b) produces:

$$\omega_o = 2\pi f_o = \sqrt{\frac{1}{L_2 C_2} \left[1 - \frac{L_2 G_2^2}{C_2} \right]} \quad (1)$$

$$Z_A(\omega_o) = R_{Ao} + jX_{Ao} = \frac{(\omega_o L_1)^2 R_{po} + j\omega_o L_1 R_{po}^2 \left[1 - \left(\frac{\omega_o}{\omega_1} \right)^2 \right]}{R_{po}^2 \left[1 - \left(\frac{\omega_o}{\omega_1} \right)^2 \right]^2 + (\omega_o L_1)^2} \quad (2)$$

where $\omega_1 = 1/\sqrt{L_1 C_1}$ and $R_{po} = R_2 + L_2 G_2 / C_2$ is the real part of Z_p at resonance. For the 1-Port AC-MSPA the reactance X_{Ao} is cancelled using an open-circuit stub, leaving $Z_A = R_{Ao}$ at resonance, which for a good match should be close to 50Ω . Repeated simulations using a range of physical parameters (PS , SL , HB) generate a characterisation data set of the corresponding electrical parameters (f_o from (1), R_{Ao} and X_{Ao} from (2) and Δf). Δf is defined as the 2:1 SWR impedance bandwidth (Return Loss = 9.54dB), and is found numerically from the $Z_A(\omega)$ data. The transmission line stub length L_s is readily calculated once X_{Ao} is known.

A Design Model for the AC-MSPA

Of interest to the antenna designer is knowledge of the physical parameters required to produce a specified electrical performance. This requires inversion of the functional relationship (from geometrical to electrical parameters) described in the previous section. A simplified approach is adopted here, where firstly the characterisation data set is searched for designs that produce $48.25\Omega \leq R_{Ao} \leq 51.81\Omega$, corresponding to a return loss at resonance in excess of 35dB, thereby eliminating one of the electrical input parameters (R_{Ao}). The following general model:

$$y = m f_o^a \Delta f^b X_{Ao}^c + y_{ofs} \quad (3)$$

is then applied to this data to find the unknown coefficient sets m , a , b , c and y_{ofs} for each $y = PS$, SL and HB ; the results are listed in Table 1.

y	m	a	b	c	y_{ofs}
PS (mm)	93.04656	-0.76354	-0.08844	0.04235	-17.94
SL (mm)	591.87768	-0.22947	0.06789	-0.04832	-346.4
HB (mm)	208.09610	-0.10929	0.04460	-0.00850	-167.0

Table 1: Values for the AC-MSPA model coefficients of (3).

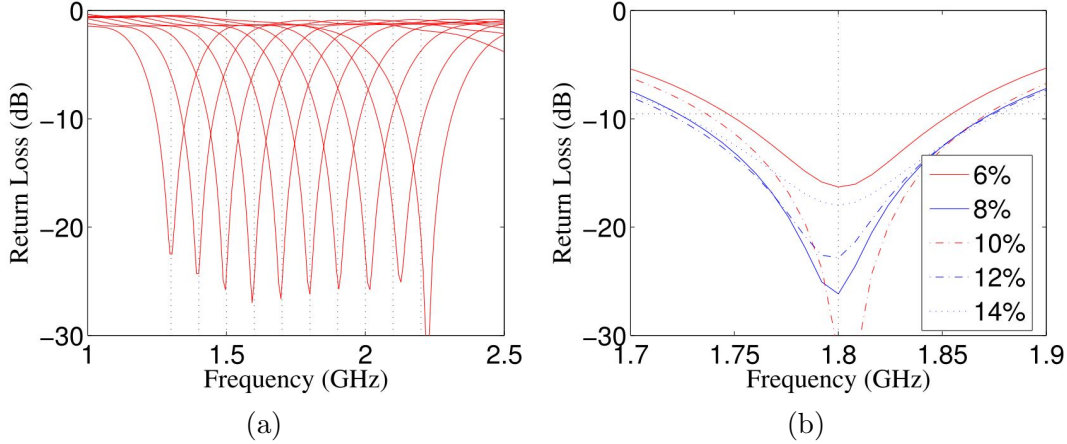


Figure 2: Return Loss frequency responses for the 14 specifications in Table 2: (a) Cases #1 to #10 where vertical dotted lines indicate the specified freqs, $\Delta f/f_o = 10\%$ (b) Cases #11 to #14 and #6 for $f_o = 1.8$ GHz and various $\Delta f/f_o$ as indicated.

Table 2 and Figure 2 summarise the model's performance for fourteen new electrical specifications (ie. not contained in the characterisation data). Cases #1 through #10 are for a sweep of centre frequencies from 1.30 GHz to 2.20 GHz with a constant fractional bandwidth $\Delta f/f_o$ of 10%. Cases #11 to #14, along with #6, are for a range of fractional bandwidths from 6% to 14%. The X_{Ao} values shown are adjusted to maintain the geometry solutions within the range of the original characterisation data. Cases #1 through #10 demonstrate excellent agreement between the specified input and simulated output centre frequencies. Cases #11 and #12 show good agreement for bandwidth, but cases #6, #13 and #14 are less accurate. However

#	Input Electrical Specifications				Output Geometry Parameters & Simulated Performance						
	f_o	Δf	$\Delta f/f_o$	X_{Ao}	PS	SL	HB	L_s	f_o	Δf	$\Delta f/f_o$
	(GHz)	(GHz)	(%)	(Ohm)	(mm)	(mm)	(mm)	(mm)	(GHz)	(GHz)	(%)
1	1.30	0.130	10	20	85.61	73.43	12.99	25.87	1.300	0.1130	8.7
2	1.40	0.140	10	20	79.28	68.43	12.12	24.01	1.396	0.1207	8.6
3	1.50	0.150	10	20	73.73	63.83	11.33	22.39	1.493	0.1278	8.6
4	1.60	0.160	10	20	68.82	59.58	10.58	20.98	1.592	0.1353	8.5
5	1.70	0.170	10	20	64.46	55.62	9.89	19.73	1.694	0.1436	8.5
6	1.80	0.180	10	20	60.54	51.92	9.24	18.62	1.798	0.1515	8.4
7	1.90	0.190	10	20	57.01	48.46	8.62	17.63	1.903	0.1594	8.4
8	2.00	0.200	10	20	53.80	45.20	8.04	16.74	2.013	0.1681	8.4
9	2.10	0.210	10	20	50.88	42.12	7.49	15.93	2.125	0.1744	8.2
10	2.20	0.220	10	15	47.41	44.61	7.39	16.35	2.224	0.1834	8.2
11	1.80	0.108	6	15	63.17	43.73	5.69	20.03	1.801	0.1077	6.0
12	1.80	0.144	8	20	62.10	45.93	7.49	18.62	1.804	0.1365	7.6
13	1.80	0.216	12	20	59.28	56.88	10.67	18.62	1.797	0.1566	8.7
14	1.80	0.252	14	25	58.96	56.76	11.56	17.31	1.800	0.1558	8.7

Table 2: AC-MSPA model performance: comparison of simulated and specified centre frequency and bandwidth values for a range of geometries (slot width = 5 mm).

this appears to be a systematic error, and may be compensated for beforehand by increasing the input bandwidth specification.

In conclusion, we present a new equivalent circuit that is simple yet yields accurate centre frequency, bandwidth and resonant frequency impedances. These can be used to generate a simple mathematical model that inverts the characterisation provided by the full-wave simulator, thereby providing a more efficient tool for AC-MSPA design.

References

- [1] R.B. Waterhouse, "Microstrip Patch Antennas: a Designer's Guide", *Kluwer Academic Publishers*, 2003
- [2] Mohamed I. Sobhy, Benito Sanz-Izquierdo, John C. Batchelor, "System and Circuit Models for Microwave Antennas", *IEEE T-MTT*, v55, n4, p729-735, April 2007
- [3] M. Dich, A. Ostergaard, U. Gothelf, "A Network Model for the Aperture Coupled Microstrip Patch", *Int. J. Micro. & MMW CAE*, v3, n4, p326-339, 1993.
- [4] Jeong Phill Kim, "Optimum Design of an Aperture-Coupled Microstrip Patch Antenna", *Microwave & Optical Tech. Letters*, v39, n1, pp. 75-78, Oct. 2003
- [5] D.M.Pozar, "A Reciprocity Method of Analysis for Printed Slot and Slot-Coupled Microstrip Antennas" *IEEE T-AP*, v34, n12, p1439-1446, Dec 1986
- [6] *www.cst.com*
- [7] Bjorn Gustavsen, Adam Semlyen, "Rational Approximation of Frequency Domain Responses by Vector Fitting" *IEEE T-Power Delivery*, v14, n3, p1052-1061, July 1999