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One-Dimensional Model of Patch Antenna

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1. Introduction

Rectangular linear-polarized patch antenna is modeled by two printed dipoles. The array of two parallel printed dipoles can be studied analytically to find consequently the radiation characteristics of the patch antenna. Closed-form formulas are presented to show the dependence of the input impedance and resonance frequency f_0 to the patch dimensions, feed point location and the dielectric thickness and permittivity. This formulation can be considered as EM-dual model of the well-known "patch cavity approach" and used indeed, to evaluate analytically the coupling effects between patches based on one-dimensional radiating elements. Comparative results between measurement, numerical simulation and analytical method are presented to show the performance of this new model.

2. Theory

It is theoretically possible to reduce and simplify the complicated-form 2D or 3D antennas with one-dimensional structures, using electromagnetic principles and current distribution on the antenna. This modeling can be done by removing and ignoring every section of the radiating surface which does not carry, relatively, RF currents [1], [2]. Generally, on the large radiating conductor surfaces the EM fields attenuate very sharply with distance. This is because of a strong current concentration at or near the edges of the conductors. Thus removing part of the inner surface to form a wire antenna should not seriously degrade the antenna characteristics.
Let's begin this procedure for a rectangular patch antenna by studying its surface current distribution. Excepted the feed point, for a linear polarized rectangular patch, the current is almost localized on the whole edges which are parallel to the antenna polarization (Fig. 1).

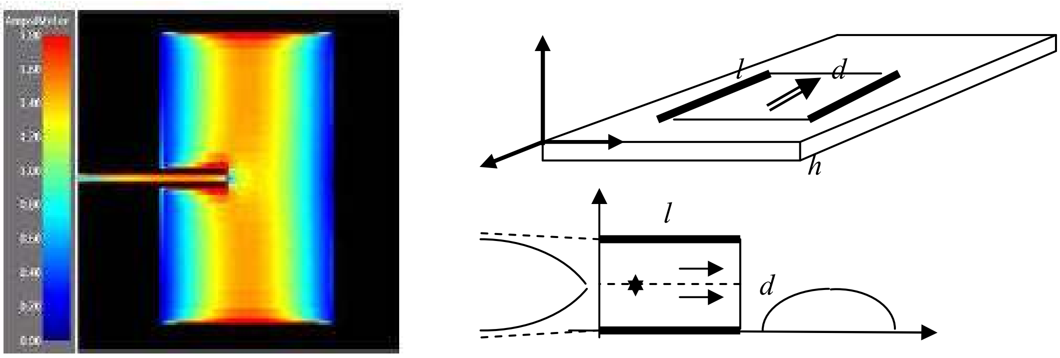


Figure 1: surface current distribution on rectangular patch antenna

According to Fig. 1, the antenna can be modeled by only two parallel printed dipoles separated by distance *d* equal to the patch width and having the patch length *l*. The current distribution along the dipoles is almost sinusoidal for a linear polarization, indeed. To find the radiation characteristics of the patch antenna, one can simply treat an array of two printed dipoles with a known geometry (*l*, *d*, *h*), substrate (*h*, ε_{eff}, λ_g) and classical sinusoidal currents.

ISBN: 978-4-88552-223-9 C3055©IEICE

The printed dipole itself can be studied analytically to evaluate the self and mutual impedances. These impedances are presented by using the "image theory" and supposing normal dipoles in near-field region [3]:

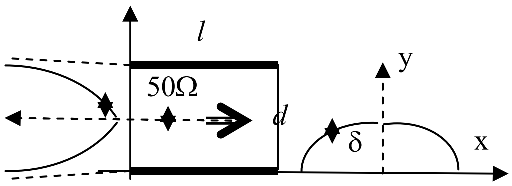
Self-impedance at resonance ; $$Z_{11} = \frac{600}{\sqrt{\varepsilon_{reff}}} \left(\frac{h}{l}\right)^2 \qquad (1)$$

Mutual-impedance (broadside) ; $$|Z_{12}| \cong \frac{40}{\sqrt{\varepsilon_{reff}}} \left(\frac{h}{d}\right)^2 \frac{\lambda_g}{d} \sqrt{1+36\frac{d^2}{\lambda_g^2}} \qquad (2)$$

The input impedance of the patch antenna can be therefore evaluated by the equivalent ($Z_{11}+Z_{12}$) of two printed dipoles. The initial value of ($Z_{11}+Z_{12}$) in formulas (1, 2) is calculated at the central point of each dipole (at the edges of the patch). But, to evaluate the patch impedance they should be transferred to the patch feed point located at the inner symmetrical axis (Fig. 2). This impedance transformation is the basic key to understand how the low impedance of a printed dipole on a thin substrate (a few Ohms [3]) can be observed even 50Ω or more at the feed point.

3. Results

Figure 2 shows the patch feed point location on its surface which is labeled on x and y directions. By assuming a known current distribution both in x and y directions [1] the transferred impedance ($d/2$, y direction / δ, x direction) of two-dipole array can be calculated at the patch feed point (* : $x = -\delta$, $y = d/2$) as follow:



$$R_{in} \text{ (patch)} \sim \{R_{11} + R_{12}\} \text{(printed dipole)} \qquad (3)$$

$$y \; ; \; |Z \text{ (centre)}| = \left|\frac{J(edge)}{J(centre)}\right|^2 |Z \text{ (edge)}| \qquad (4)$$

$$x \; ; \; |Z (\delta = 0)| = \mathrm{Cos}^2 \left(2\pi \frac{\delta}{\lambda_g}\right) |Z (\delta)| \qquad (5)$$

Figure 2: impedance transformation in x and y direction on a patch antenna

The current distribution a long the patch is quasi-sinusoidal and the impedance transformation in this direction describes as in formula 5 [3]. For the current density J as a function of y, there is not a clear mathematical equation however by using the model a very useful relation is deduced:

$$\text{(1), (2) and (4)} \Rightarrow \left|\frac{J(centre)}{J(edge)}\right|^2 \sim \frac{1}{\sqrt{\varepsilon_{reff}}} \left\{\left(\frac{h}{l}\right)^2 + \alpha\left(\frac{h}{d}\right)^2\right\} \text{ where } 0.1 < \alpha < 0.2 \qquad (6)$$

According to relation (6), a very thin substrate having small ε_r causes strong current decrease moving from edges to the centre of the patch (y-direction) and consequently the observed impedance at this point is relatively raised. Simultaneously, a thick strong ε_r substrate needs a more off-central shifted (δ in x-direction, formula 5) feeing to achieve standard impedance 50Ω.
The immediate application of this model is the deduction of an analytical formulation for the mutual impedance between two rectangular patches [2] which is a set of a few printed dipoles. According to formula 2, for the very close broadside patches ($d \ll \lambda_g$) the mutual impedance is proportional to d^{-1} , d^{-3} and by the way, for the longer distances ($2d > \lambda_g$) mutual impedance changes its behavior and is proportional to d^{-2}.

3.1 Comparison between measurement and analytical method

An experimental set-up has been elaborated to evaluate the analytical formulation. The rectangular patches are chosen to have their resonance at 2 GHz and the mutual impedances have been evaluated at this frequency as a function of nearest distance between the patches in broadside, collinear and echelon positions. The self-impedance of antenna is 50Ω which imposes together with the resonance frequency the exact emplacement of the feeding point. The patches are separately printed on a thin substrate h = 0,8mm, ε_r = 2,2 with similar dimensions: $l = d$ = 42mm (Fig. 3). The complex mutual impedances are presented entirely with their module in Ohms |Ω| and phase in degrees <ϕ°.

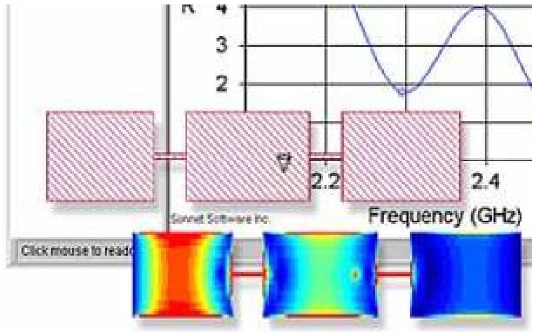


Figure 3: SMA-coaxial fed patch antenna and a schema of current distribution on collinear patches

Table 1: mutual impedance between two rectangular patch antennas, broadside position (H-plan)

Distance mm	Measurement |Ω| < ϕ°	Numerical |Ω| < ϕ°	Analytic |Ω| < ϕ°
14	28 < 198	26 < 186	33 < 243
18	---	22 < 175	21 < 230
22	15 < 171	20 < 165	18 < 210
26	---	16 < 155	17 < 191
32	9 < 150	13 < 138	12 < 162

Table 1 shows the comparative results between measurement, analytical formulas and numerical results by a commercial simulator in broadside position. All the measurements are done for the SMA-coaxial fed patches and it is necessary to take into account the parasitic effect of this connector on the antenna input impedance [4]. The agreement between experimental and analytical results is relatively good for the module of mutual impedance. Nevertheless, for the smaller distances the phase deviation between measurement, simulation and analytical results is more important. This could be controlled by interring the negligible terms in formula 2 and a more effective meshing in numerical simulation.

A few data are presented in Table 2 for the collinear arrangement and an interesting special case (*) for a 30° in-echelon position. Again a good agreement is observed for the modules of analytical and experimental results.

Table 2: mutual impedance between two rectangular patch antennas, collinear position (E-plan)
* unique case, 30° in-echelon

Distance mm	Measurement $\|\Omega\| < \phi°$	Numerical $\|\Omega\| < \phi°$	Analytical $\|\Omega\| < \phi°$
14	6 < 128	11 < 128	7 < 165
22	5 < 120	9 < 108	5< 140
14*	8 < 168	20 < 170	9 < 280

The analytical formulation demonstrates its good performance for the rectangular patches despite of its simplicity. However, it could be an interesting challenge to develop relevant formulas for more sophisticated antenna arrangement and even in large printed antenna arrays.

4. Conclusion and Perspectives

Rectangular linear polarized patch antenna is modeled by two printed dipoles. The model can be easily used to evaluate the mutual impedance between patch antennas as well as the self-characteristics of the patch. Indeed, the one-dimensional approach is especially helpful to calculate the coupling effects between two patches in-echelon position or even in a 3D geometry. So far, the method could be extended to 3D antennas to find some relevant one or two-dimensional models and for the many-body array antennas.

Acknowledgment

This research project was supported in part by the MIC (Ministry of Information and Communication) – Korea, under the Foreign Professor Invitation Program of the IITA (Institute for Information Technology Advancement).

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