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Analysis of an E-shaped Patch Using CMA and CMT

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***Abstract*—The impedance bandwidth of a microstrip patch antenna may be increased by additional resonances in the antenna structure. This work uses Characteristic Mode Analysis to show that the E-shaped patch operates in this manner and that Coupled Mode Theory governs its operation.**

***Keywords*—E-shaped patch antenna, characteristic mode analysis, coupled mode theory**

I. Introduction

The impedance bandwidth (BW) of a microstrip patch antenna may be increased by additional resonances in the antenna structure. As shown in this paper, the well-known E-shaped patch [1] operates in this manner and is governed by Coupled Mode Theory (CMT). Characteristic Mode Analysis (CMA) was employed in [2] to show CMT governs a distinct but closely related structure, the U-slot patch antenna [3].

CMA [4] is a modal decomposition based on the method of moments (MoM) wherein a set of basis currents J_n result from $[X]\,J_n = \lambda_n\,[R]\,J_n$ where $[Z] = [R] + j[X]$ is the MoM impedance matrix and λ_n is the eigenvalue. Currents on a structure driven by a source $E_{\text{tan}}^{\text{i}}$ may be represented as a linear combination of modes: $J_{\text{total}} = \sum_n \alpha_n J_n$ where α_n are the modal weighting coefficients (MWCs). Thus, the driven admittance of a structure is the sum of all modal admittances. CMT describes the dynamics of a system of two coupled resonators as the superposition of two coupled modes, an in-phase and anti-phase mode, with respective lower- and higher-frequencies. The coupled mode frequencies $\omega_\pm$ are related to the uncoupled mode frequencies $\omega_{1,2}$ by [5]:

$$\omega_\pm = \omega_0 \pm \sqrt{\left(\frac{\omega_2 - \omega_1}{2}\right)^2 + |K|^2} \qquad (1)$$

where $\omega_0 = (\omega_2 + \omega_1)/2$ and K is an un-normalized coupling coefficient.

Because the E-shaped patch is a special case of the U-slot patch (see Fig. 1), much of what is known about the U-slot patch [2] applies to the E-shaped patch. This paper shows that like the U-slot patch, CMT governs the E-shaped patch, however, the coupling in the latter is substantially *asynchronous* (i.e., $\omega_1 \neq \omega_2$). This knowledge can be used to develop a design methodology for E-shaped patches similar to that of [2].

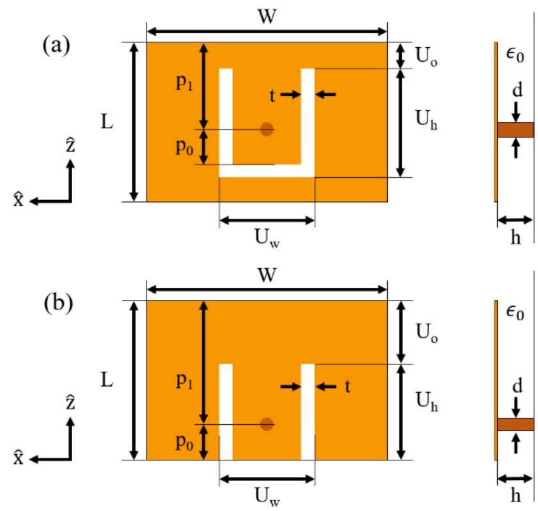

Figure 1. The E-shaped patch (b) is a special case of the U-slot patch antenna (a) wherein $U_0 = L - (U_h - t)$. As such, much of what is known about U-slot patches [2] applies to the E-shaped patch. The dimensions for (b) from [1] are: (W, L, h, U_h, U_w, p_0, d) = (70, 45, 10, 35, 30, 10, 3) mm.

II. Characteristic Mode Analysis

The geometry of Fig. 1(b) is solved in FEKO [6], a MoM code with CMA. The systematic analysis process described in [7] is used in what follows. A 1V gap source, which is used for the driven solution as well as calculating MWCs, is located at the base of the probe. CMA results show only two modes (modes 1 and 2) are strongly excited near the full-wave driven impedance bandwidth (10 dB BW $2.26 - 3.19$ GHz); they are resonant ($\lambda_n = 0$) at $f_- = \omega_-/(2\pi) = 2.21$ GHz and $f_+ = \omega_+/(2\pi) = 2.97$ GHz. Modal charge distributions are shown in Fig. 2; we designate the in-phase mode as that with the lower resonant frequency. The parallel combination of the modal admittances of these two modes closely replicates the full-wave driven impedance locus as seen in Fig. 3.

CMA is performed on the patch *with no slot* and the slot *with no patch* (the latter is referred to as the "uncoupled slot resonator" [2]). These geometries are shown in Fig. 4. Together they represent the full E-slot patch geometry of Fig. 1(b) when they are superposed using their common probe geometry to "register" each with respect to the other. Note the U-shaped slot of Fig. 4(b) approximates a half-infinite ground plane (i.e., PEC for $z > 0$ *only*)—for which no Green's function is available. The resulting resonances are $f_{\text{slot}} = 2.42$ GHz $\equiv f_1$ and

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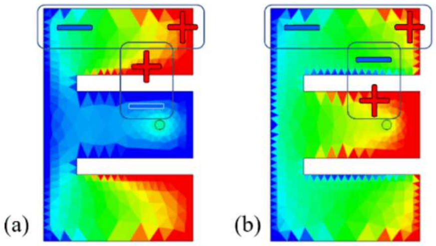

Figure 2. CMA charge distributions for (a) the in-phase, lower frequency mode 1 and (b) the anti-phase, higher frequency mode 2.

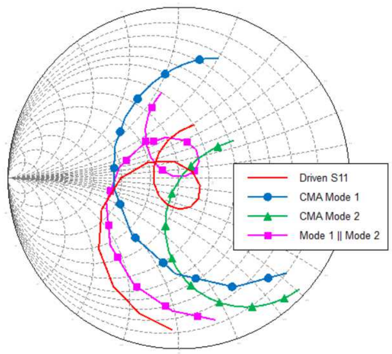

Figure 3. When added in parallel, the admittances of CMA modes 1 and 2 closely replicate that of the full-wave driven structure [1].

$f_{\text{patch}} = 2.79$ GHz $\equiv f_2$. These frequencies differ significantly; any coupling between the two is *asynchronous*.

Resonant modal nearfields for the uncoupled patch, E_1 and H_1, and uncoupled slot, E_2 and H_2, are calculated in a $140 \times 90 \times 20$ mm volume encompassing the patch and slot. Hong [8] gives the coupling between two resonators as:

$$\kappa = \kappa_E + \kappa_H = \frac{\int \epsilon E_1 \circ E_2 \, dV}{\sqrt{\int \epsilon |E_1|^2 \, dV \times \int \epsilon |E_2|^2 \, dV}} + \frac{\int \mu H_1 \circ H_2 \, dV}{\sqrt{\int \mu |H_1|^2 \, dV \times \int \mu |H_2|^2 \, dV}} \quad (2)$$

where dV is the infinitesimal volume element and ϵ and μ represent the spatial distribution of permittivity and permeability, respectively. Given full-wave (as opposed to static) near-field data, κ_E and κ_H are complex; we use $|\kappa|$ in what follows.

In [2], it was shown that for the synchronous case:

$$K \sim \kappa\omega_0/2; \quad (3)$$

we use it here judicously. We may use nearfield data of the uncoupled slot and uncoupled patch resonator with (2) and (3) to estimate the *coupled* frequencies $\omega_\pm$ of the full E-shaped patch structure via (1). For the uncoupled geometries of Fig. 4, this procedure yields $|\kappa| \sim 0.216$ and $f_- = 2.27$ GHz and $f_+ = 2.94$ GHz—within a few percent of the CMA-calculated values of the full structure of Fig. 1(b). Next, the parameter U_w was varied $\pm 10\%$ and the above process repeated; we find $|\kappa|$ is a weak function of U_w, in contrast to the U-slot patch [2]. Results are shown in Fig. 5; we find good agreement between the CMA-calculated coupled resonances of the full structure

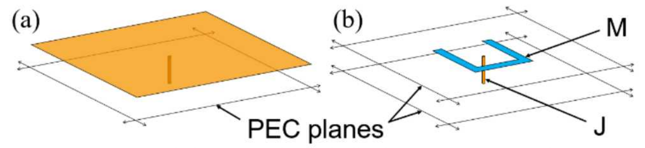

Figure 4. Uncoupled (a) patch and (b) slot resonators; when superposed the two geometries represent Fig. 1(b) [1]. CMA near-fields of each structure are calculated and used in (2) to estimate the coupling coefficient κ.

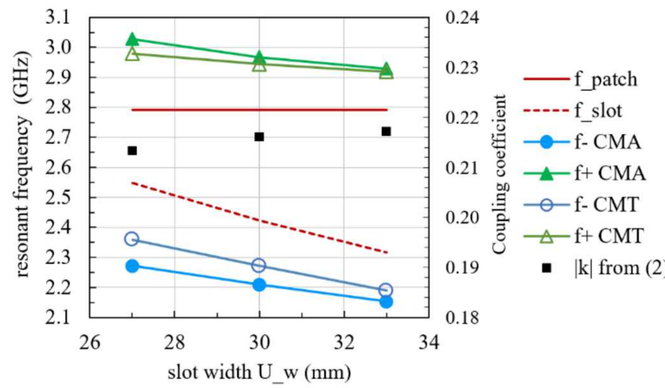

Figure 5. CMA resonant frequencies of the uncoupled patch and uncoupled slot as U_w is varied (all other dimensions held constant), along with the CMA-calculated mode 1 & 2 (coupled) resonances of the full E-shaped patch. CMT-based estimates of the coupled frequencies are within a few percent of the CMA-calculated values.

and those predicted by CMT; this is strong evidence that CMT governs E-shaped patch operation. Because the coupling coefficient is substantially constant, changes in the coupled resonances $f_\pm$ in Fig. 5 are due primarily to changes in the uncoupled slot resonance.

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