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Analysis of a U-Slot Patch Using Characteristic Mode Analysis and Coupled Mode Theory

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Abstract—**Patch antennas incorporating a U-shaped slot are well-known to have relatively large (about 30%) impedance bandwidths. However, a theory of operation for these devices has remained elusive more than 20 years after their introduction. This paper uses Characteristic Mode Analysis to show a classic U-slot patch geometry supports in-phase and anti-phase coupled modes that occur within Coupled Mode Theory.**

Index Terms—**Broadband antenna, microstrip antenna, U-slot antenna, characteristic mode analysis, coupled mode theory**

I. INTRODUCTION

As first demonstrated in [1], the addition of a U-shaped slot significantly increases the otherwise narrow impedance bandwidth of a probe-fed microstrip patch antenna. It has been hypothesized that this is due to the existence of two resonances—that of the patch and that of the U-shaped slot. Several researchers have reported observations of, and empirical design algorithms for, the U-slot patch. One such study [2] gave qualitative guidelines regarding how the impedance locus behaved in response to dimensional changes. Another study [3] found empirical relations between design dimensions and the frequencies of the reflection coefficient magnitude minima. In [4], investigators used parametric numerical studies to characterize the response of the impedance locus to dimensional changes and gave an algorithm that yields initial design dimensions. Another study [5] observed that the ratios of acceptable design dimensions were substantially constant with changes in substrate permittivity.

As in [6], this work uses Characteristic Mode Analysis (CMA) and Coupled Mode Theory (CMT) to reveal some of the principles that govern the classic U-slot patch geometry [1]. CMA is a modal decomposition technique based on the method of moments (MoM) [7-9]. CMT states the dynamics of a system of two coupled resonators as the superposition of two *coupled modes*, an in-phase and anti-phase mode, each with different frequencies [10].

The coupled mode frequencies, ω_+ and ω_-, are related to the uncoupled mode frequencies, ω_1 and ω_2, by [11]:

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

where $\omega_0 = (\omega_2+\omega_1)/2$ and K is an un-normalized coupling coefficient. Given synchronous coupling ($\omega_1 = \omega_2$), a normalized coupling coefficient $\kappa \sim \omega_0 K/2$ may be calculated from the coupled mode resonant frequencies via [12]:

$$\kappa = \frac{{\omega_+}^2 - {\omega_-}^2}{{\omega_+}^2 + {\omega_-}^2}. \qquad (2)$$

II. CHARACTERISTIC MODE ANALYSIS OF A U-SLOT PATCH

A commercial MoM/CMA solver [13] was used to analyze the classic U-slot patch geometry given in [1]. CMA modes 1 and 3 (the mode numbers are arbitrary) are resonant at 0.80 GHz and 1.05 GHz. The reflection coefficients of these modes in a system impedance of 50 Ω are plotted in Fig. 1. According to CMA, the total admittance of a structure is the parallel combination of mode admittances, and thus the reflection coefficient of the parallel combination of CMA modes 1 and 3 is also plotted in Fig. 1. We see this agrees well with the admittance calculated by the driven MoM solve (i.e., an edge port driven by a 1 Volt source), also shown in Fig. 1, differing only by a small capacitive susceptance attributed to sub-resonant higher order characteristic modes excluded from the limited parallel combination of CMA modes 1 and 3. These modes have similar broadside radiation patterns, resulting in a stable radiation pattern throughout the entire impedance bandwidth, as shown in Fig. 2.

Normalized charge distributions at phase angle $\phi = 90°$ for CMA modes 1 and 3 at their respective resonant frequencies are shown in Fig. 3. The expected charge accumulation is visible at the edges of the patch and the center of the slot, however, the spatial orientation of these distributions with respect to the other differs between the two CMA modes. For CMA mode 1, the patch and slot charge distributions are in phase; for CMA mode 3, the patch and slot charge distributions are anti-phase. The presence of such modes strongly suggests that coupled mode theory is relevant to the operation of the U-slot patch.

Further evidence of this is found in the behavior of the resonant frequencies of CMA modes 1 and 3 in response to changes in coupling factor. According to (1), a larger coupling factor results in a larger difference between the coupled mode resonant frequencies. This behavior is indeed present in the U-slot patch design of [1], as shown in Fig. 4. Here, the width of the "U" (the 2.70" dimension in [1]), denoted U_w, is varied while the total slot length remains constant. As can be seen in Fig. 4, the ratio U_w to the width of the patch (the 8.65" dimension in [1]), denoted W, roughly corresponds to the coupling coefficient calculated by (2). This can be understood by noting that the fraction of TM_{01} mode patch current intercepted by the slot is approximately U_w/W.

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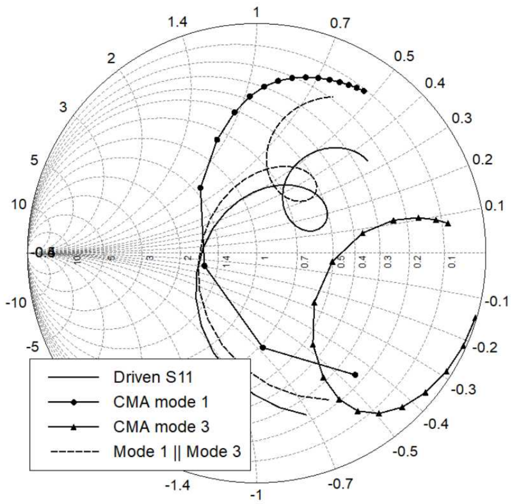

Figure 1. The admittance of the parallel combination of CMA modes 1 & 3 agrees well with the driven admittance locus of the U-slot patch.

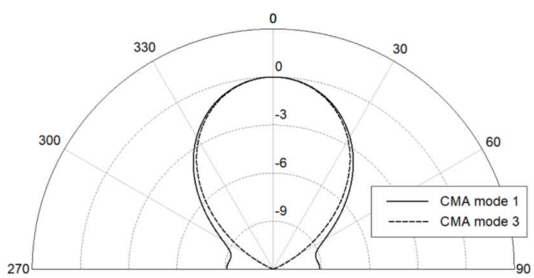

Figure 2. E-plane cuts of CMA mode 1 & 3 far-fields show each has a broadside radiation pattern (each normalized to 0 dBi directivity).

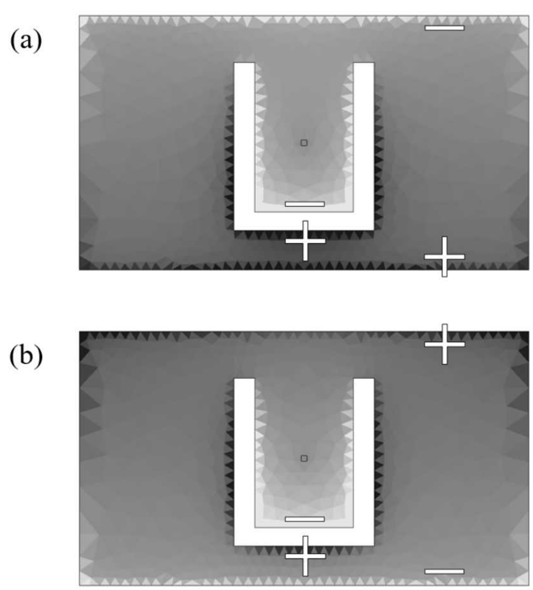

Figure 3. Normalized charge distributions of CMA modes 1 & 3 at phase angle 90° at their respective resonant frequencies show that the patch and slot charge distributions are (a) in-phase for CMA mode 1 and (b) anti-phase for CMA mode 3.

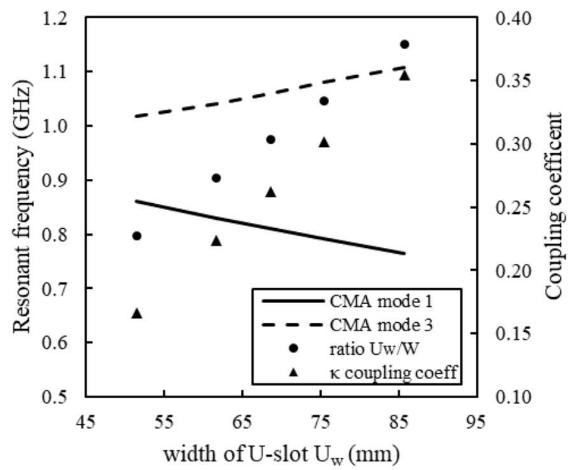

Figure 4. Left axis (solid and dashed lines): An increase in frequency separation of the in-phase (CMA mode 1) and anti-phase (CMA mode 3) resonances with increasing U-slot width (while keeping the total slot length constant) is evidence for the relevance of coupled mode theory to the operation of the U-slot patch. Right axis (● and ▲ data points): the ratio U_w/W corresponds approximately to the coupling coefficient κ, as calculated by (2).

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