Ultra-Wide Bandwidth Enhancement of Single-Layer Single-Feed Patch Antenna Using the Theory of Characteristic Modes

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Abstract **─** The Theory of Characteristic Modes (TCM) is proposed as a systematic approach to antenna design to achieve the goal of finding the antenna structure with optimum broadband behavior. This theory provides a physical insight to the radiating nature of microstrip patch antennas and reduces the design optimization time. In this work, the resonant behavior of the highly radiating structure of the single U-slot rectangular patch on a single-layer $\varepsilon_r = 4.4$ substrate is analyzed using TCM. Modal analysis of this single-layer structure with different single feed excitations concludes that VSWR ≤ 2 impedance bandwidth in the order of 96% can be achieved with a single T-probe feed. Experimental results, included here, show VSWR ≤ 2 impedance bandwidth in the order of 71%.

Index Terms **─** Bandwidth broadening, characteristic mode analysis, L-probe, microstrip patch antennas, T-probe, theory of characteristic modes, U-slot, UWB.

I. INTRODUCTION

The need for antennas with high bandwidth is continuing to fuel a lot of research especially in the fields of radar, wireless communication and medical imaging. Microstrip patch antennas are a class of antennas that exhibit low-profile, compact, conformal, cost-effective, and easy-to-fabricate designs. Despite these advantages, microstrip patch antennas suffer from a major drawback, which is narrow bandwidth. For the past couple of decades, extensive research has been dedicated to the area of bandwidth broadening techniques of microstrip patch antennas. Some of these techniques are by means of introduction of parasitic elements and patch slots, which introduce additional resonances in addition to the main patch resonance. Another technique is by means of thick substrates of low permittivity, which will have the side effect of introducing higher inductive reactance due to the longer coaxial feed probe. Some of the patch slot geometries found in the literature are: square, rectangular, triangular, circular, elliptical, E-slot, U-slot, V-slot, and more [1, 2]. Although it is generally understood that patch slots introduce new resonances that contribute to broadening the bandwidth, it is not well understood why some patch slots present better bandwidth than others. A valuable tool that is helping antenna designer's gain better understanding and physical insight of the radiating nature and resonant behavior of the microstrip patch antenna is the TCM [3, 4]. By understanding the resonant behavior of the different patch slot geometries and other antenna elements, novel antenna designs with the most resonant structures can be proposed to achieve the most radiation and impedance bandwidth.

In recent studies [5-7], we utilized TCM to characterize the resonant behavior of different patch slot geometries, substrate permittivities and ground sizes independent of the feeding element to identify the structures which are more resonant, and hence, contribute significantly to the radiated fields. It was concluded that a single U-slot rectangular patch on a single-layer substrate with relative permittivity of 4.4 and loss tangent of 0.02 will result in a highly radiating structure.

It is the aim of this paper to expand on these recent studies [5-8] and to find the ideal excitation feed to excite the highly radiating structure of the U-slot rectangular patch on $\varepsilon_r = 4.4$ substrate to achieve the most radiation and impedance bandwidth. TCM will be utilized once more to analyze some of the different excitation feeds found in the literature [9] to determine the least reactive excitation feed structure, which will excite the modes contributing to the optimum resonant behavior of the U-slot patch antenna.

II. MODAL ANALYSIS OF EXCITATION FEEDS FOR U-SLOT PATCH ANTENNA

Modal significance is defined as the normalized amplitude of the characteristic modes. Modes where the modal significance is close to 1 indicate that they contribute significantly to radiation, whereas modes with modal significance close to 0 indicate they do not [4]. Therefore, modal significance gives the antenna designer physical insight on the resonant behavior of an antenna structure independent of the source excitation.

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Before we model the highly radiating structure of U-slot patch and ε_r = 4.4 substrate with an excitation feed, we need to first investigate which eigenmodes are resonating on this structure. In Fig. 1, the modal significance of the top 6 significant eigenmodes is shown. It is shown that modes 1, 3, and 4 contribute the most to radiation since their modal significance is close to 1 over the frequency range 2.5-8.5 GHz. Higher order modes 5 and 6 contribute minimally in the higher frequencies. So, prospective excitation sources will aim to excite all or some of the resonating eigenmodes (1, 3, and 4) in the antenna structure.

Figure 2 shows the characteristic currents for modes 1, 3, and 4 at 5.0 GHz. The location of maximum current distribution, where it is desirable to excite the patch, is denoted by the concentrated red color in Fig. 2. The common location for maximum current distribution between all three modes is marked by the dotted black circles in Fig. 2 and is found to be at the base of the U-slot and the inner edge of the U-slot arm.

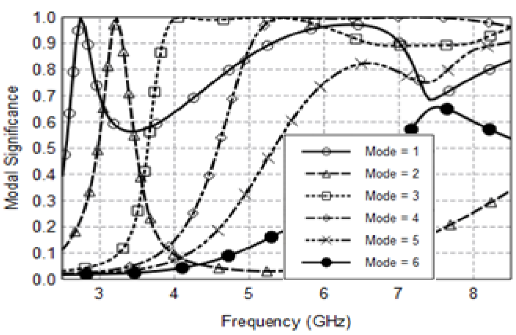
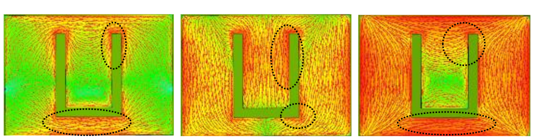


Fig. 1. Modal significance for U-slot patch antenna with ε_r = 4.4 substrate.



(a) (b) (c)

Fig. 2. Characteristic currents of U-slot rectangular patch antenna on ε_r = 4.4 substrate at 5.0 GHz for: (a) mode 1, (b) mode 3, and (c) mode 4.

To find an ideal source feed which will excite the most modes, modal analysis of the U-slot rectangular patch antenna on the ε_r = 4.4 substrate with tan(δ) = 0.02 is performed with 3 different probe feeds, namely the conventional vertical probe, the L-probe, and the T-probe, shown in Fig. 3. The U-slot patch antenna and probe dimensions, designed using the method of dimensional invariance [1] for a 3.9 GHz design frequency, are shown in the first three columns in Table 1 for each of the probes. The probe radius is defined as r_p. The x- and y-axis positions of the probe are defined as x_p and y_p, respectively. The probes are placed at the location of maximum current distribution marked in Fig. 2. The horizontal and vertical arms of the L-probe and T-probe are defined as L_h and L_v, respectively. The horizontal arm of the T-probe is symmetric, i.e., its length on the left side of vertical arm is equal to its length on the right side of vertical arm, which is equal to 3.84 mm.

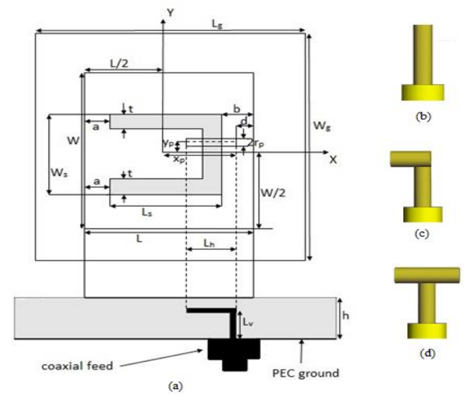


Fig. 3. (a) Geometry of rectangular patch antenna with U-slot, (b) vertical probe, (c) L-probe, and (d) T-probe.

Table 1: U-slot patch antenna dimensions in mm for different feed probe designs

	Vertical Probe (Sim.)	L-Probe (Sim.)	T-Probe (Sim.)	T-Probe (Fabricated)
a	2.25	2.25	2.25	4.38
b	2.25	2.25	2.25	4.38
W	20.25	20.25	20.25	39.48
L	14.62	14.62	14.62	28.51
L_s	10.14	10.14	10.14	19.78
t	1.13	1.13	1.13	2.21
W_s	7.87	7.87	7.87	15.35
W_g	140.17	140.17	140.17	139.41
L_g	134.54	134.54	134.54	128.44
h	7.62	7.62	7.62	15.35
r_p	1	1	1	0.65
x_p	6	4.81	4	10.95
y_p	5	1	1	0
L_h	----	3.84	3.84	2.99x2.28
L_v	7.62	6.53	6.15	12.80
d	1.31	2.5	3.31	3.31

In [8], we performed a modal excitation analysis over the selected frequency range 2.5-8.5 GHz on the U-slot rectangular patch slot and ε_r = 4.4 substrate with vertical probe, L-probe, and T-probe to determine which source feed excites the modes 1, 3, and 4, which contribute to the optimum resonant behavior. It was found that mode 3 is the main mode excited by the conventional vertical probe in the frequency range 2.5-5.7 GHz. Mode 3 is the main mode excited by the

L-probe in the frequency range 2.5-6.1 GHz. Modes 3, 4, and 6 are the main modes excited by the T-probe in the frequency range 2.5-7.0 GHz. Consequently, the T-probe excites the most number of modes over the largest frequency range, and hence, is expected to achieve the highest impedance bandwidth.

In Fig. 4, the modal significance of each of the three probes is shown. The non-excited probe structures are modeled independent of the other antenna elements, i.e., the U-slot patch, substrate, and ground plane. For the vertical probe, in Fig. 4 (a), mode 1 is the contributing mode maxing out at modal significance equal to 0.08. For the L-probe, in Fig. 4 (b), mode 1 is the contributing mode maxing out at modal significance close to 0.16. For the T-probe, in Fig. 4 (c), modes 1 and 2 are the contributing modes maxing out at modal significance close to 0.20. Compared to the other two probes, the T-probe has more modes with higher modal significance which indicates that it is the least reactive feeding structure. This is a desirable feeding structure feature and also explains why the T-probe is expected to achieve the highest impedance bandwidth. The fact that the modal significance of all the probes is relatively low at less than 0.20 indicates that they will not contribute much to the radiation of the entire antenna, which is another desirable feature in feeding structures.

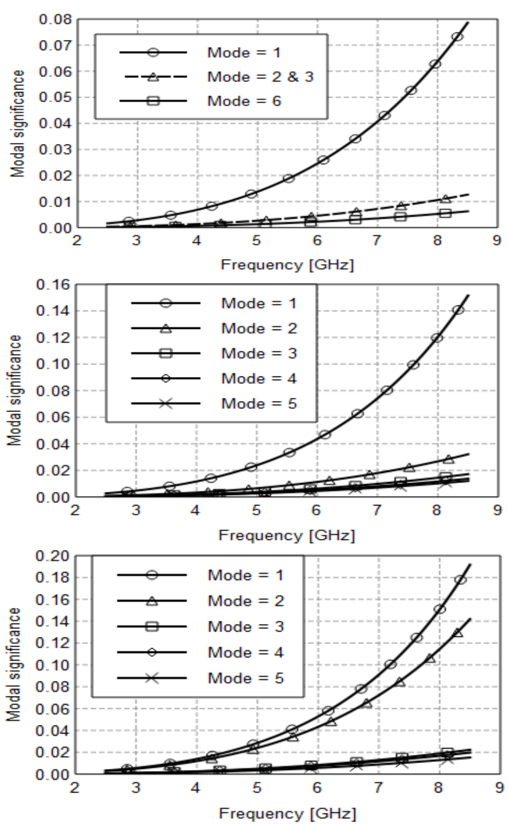


Fig. 4. Modal significance of different excitation feeds: (a) vertical probe, (b) L-probe, and (c) T-probe.

III. OPTIMIZED IMPEDANCE BANDWIDTH OF U-SLOT PATCH ANTENNA

Figure 5 shows the VSWR ≤ 2 bandwidth for the 3.9 GHz U-slot patch design with 3 different probes (dimensions shown in the first three columns of Table 1). Results from two electromagnetic solvers, namely FEKO FEM and HFSS FEM, are shown for validation purposes. The vertical probe in Fig. 5 (a) shows VSWR ≤ 2 bandwidth of 21% between 3.55 GHz and 4.38 GHz. The L-probe feed in Fig. 5 (b) shows VSWR ≤ 2 bandwidth of 82% between 2.74 GHz and 6.58 GHz, and the T-probe feed in Fig. 5 (c) shows VSWR ≤ 2 bandwidth of 96% between 2.86 GHz and 8.16 GHz. The simulation results of the two solvers are in good agreement.

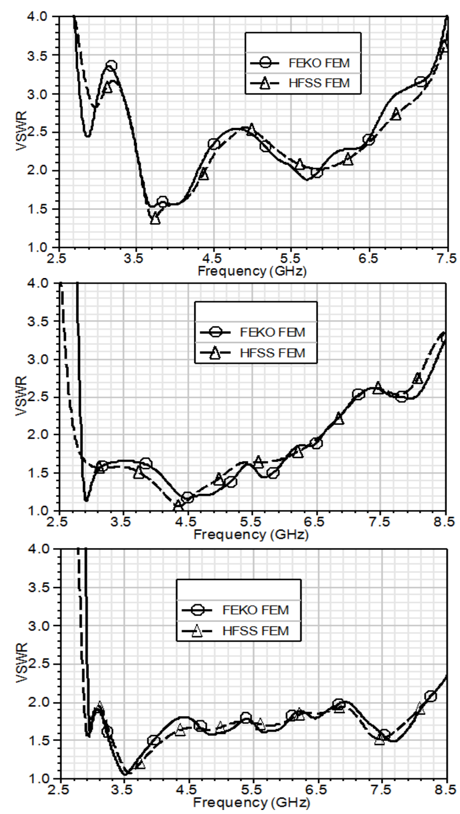


Fig. 5. Simulated VSWR for U-slot patch antenna with different excitation feeds: (a) vertical probe, (b) L-probe, and (c) T-probe.

The small substrate thickness of 7.62 mm used in the T-probe fed antenna design simulation of Fig. 5 (c) was not available for fabrication. Also, the horizontal probe arm of the T-probe was modeled as a rectangular PEC sheet sandwiched between two substrate layers due to lack of proper instrumentation to fabricate a T-shaped probe. Therefore, a bigger patch antenna with thicker multilayered substrate was fabricated for a 2.0 GHz design frequency, instead. The dimensions of the fabricated T-probe fed U-slot patch antenna are shown in the rightmost fourth column of Table 1. Figure 6 shows the measured and simulated VSWR ≤ 2 bandwidth of the fabricated antenna. As seen in Fig. 6, measured VSWR ≤ 2 bandwidth of over 71% between 1.8 GHz and 3.8 GHz is realized, though bandwidth can be improved between 2.2 and 2.4 GHz. Also, a higher VSWR ≤ 2 bandwidth between 1.8 and 4.8 GHz could be realized if it was not for the oscillations around 2.3, 3.9, and 4.5 GHz. These oscillations are mainly due to the thicker substrate used in fabrication which introduces more surface waves that scatter at substrate edges. The slight discrepancy between the measured and simulated results in Fig. 6 can be attributed to fabrication inaccuracies and manufacturing tolerances, otherwise the pattern demonstrated by the two curves mostly agree.

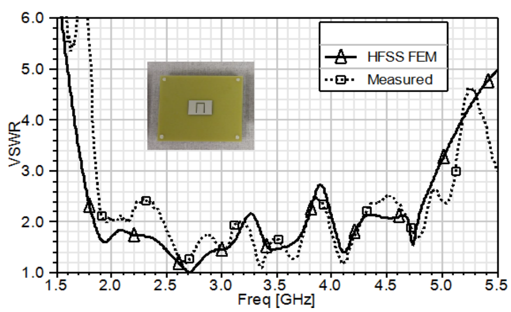


Fig. 6. Measured vs simulated VSWR of fabricated T-probe fed, U-slot microstrip patch antenna with $\varepsilon_r = 4.4$ substrate. Inset: image of fabricated antenna.

IV. CONCLUSION

In this paper, the Theory of Characteristic Modes has been used to find the ideal excitation feed to excite the highly radiating structure of the U-slot rectangular patch on $\varepsilon_r = 4.4$ substrate to achieve the most radiation and impedance bandwidth. Different excitation feeds, namely the vertical probe, L-probe, and T-probe were analyzed to determine the least reactive excitation feed structure, which will excite the modes contributing to the optimum resonant behavior of the U-slot patch antenna. Simulated and experimental results show that a single T-probe feed excites the most number of modes and achieves impedance bandwidth in excess of 70%.

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