

Modal Analysis in a Full-wave Electromagnetic Simulator for Dual-Band Microstrip Antenna Design

Ngozi Peggy Udeze, Akaa Agbaeze Eteng

Abstract— The analysis of resonant modes simplifies the optimization process required in the design of microstrip antennas. This approach is bolstered by the incorporation of characteristic-mode analysis (CMA) tools in more recent versions of numerical electromagnetic solvers. However, in cases where automated CMA tools are unavailable, physical insights into the antenna behavior can still be obtained by a modal analysis of full-wave electromagnetic simulation results. This paper demonstrates an approach to optimize a simulation model of a dual-band microstrip antenna by analysing the resonant eigenmodes excited on the antenna structure. The analysis enables the selection of appropriate antenna geometries to be optimized in order to achieve the required performance. The optimized antenna structure is simulated in two different numerical electromagnetic solvers, and comparable results are obtained in each case.

Index Terms— characteristic-mode analysis (CMA), dual-band, eigenmodes, microstrip antennas, resonance.

1 INTRODUCTION

DUAL-band microstrip antennas have been a subject of popular research interest, owing to their applicability in multiple scenarios where two operating frequencies are required [1], [2], [3]. Among the various techniques for enabling dual-band functionality in microstrip antennas, the incorporation of U-slots on the antenna radiating patch leads to relatively simple designs [4], [5], [6].

A typical approach to optimizing a U-slot-based microstrip antenna would require parametric studies to establish the impact of various parameters on the antenna performance [5]. Apart from leading to a lengthy optimization process [7], the success of this approach largely depends on exhaustive parametric studies, as well as the designer's intuition and prior experience [8]. Consequently, characteristic-mode analysis (CMA) has been employed as an alternative design methodology, which provides physical insights to enable a deterministic design approach [4], [7], [8].

2 METHODOLOGY

2.1 Background

As summarized in [7], characteristic mode analysis is based on relating the surface currents J to the electric fields producing them. This can be reduced to a problem relating surface currents and impedances, leading to an eigenvalue problem [9]:

$$Z(J_n) = v_n R(J_n), \quad n = \{0, \infty\} \quad (1)$$

where J_n are eigenmodes, and v_n are the complex eigenval-

ues. Z is the impedance operator and can be expressed in rectangular form as

$$Z = R + jX. \quad (2)$$

With

$$v_n = 1 + j\lambda_n, \quad (3)$$

the eigenvalue problem can be reduced by substituting equations (2) and (3) for Z and v_n in equation (1), thereby yielding the eigenvalue problem

$$X(J_n) = \lambda_n R(J_n), \quad (4)$$

where λ_n are the eigenvalues. Consequently, for the eigenmodes J_n , corresponding eigenvalues can be determined as

$$\lambda_n = X/R \quad (5)$$

Since $-\infty < \lambda_n < \infty$, discrete eigenvalues are weighted using the modal significance:

$$MS_n = |1/(1 + j\lambda_n)|, \quad (6)$$

so that $0 < MS_n < 1$.

We note that equation (5) can be obtained from the impedance matrix in a full-wave electromagnetic antenna simulation. However, the excitation of an antenna structure in a full-wave simulator causes a merging of the discrete eigenmodes. Consequently, a continuous modal significance function MS , based on the composite eigenvalue function λ_f , can be substituted for discrete modal significances MS_n , so that:

$$MS = |1/(1 + j\lambda_f)| \quad (7)$$

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where λ_f is a combination of all λ_n over the frequencies of interest f .

2.2 Antenna Design

In this demonstration, an antenna for dual-band operation at 2.4 GHz and 5 GHz is synthesized in a full-wave numerical electromagnetic simulator CST Microwave Studio v.2015©, which is based on the finite integration technique (FIT). The dual-band antenna design begins by establishing the dimensions of the antenna radiating patches at 2.4 GHz and 5 GHz. Using design equations for quarter-wave antenna designs [10], the length of each side of a square patch is computed using

$$l = \frac{\lambda_f}{4\sqrt{\epsilon_{reff}}} - \Delta l \tag{8}$$

λ_f represents the wavelength, which is calculated for each resonant frequency f_r as

$$\lambda_f = c/f_r, \tag{9}$$

where c is the speed of light in a vacuum. Using an antenna substrate whose thickness is h , the effective dielectric constant ϵ_{reff} is computed using

$$\epsilon_{reff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + 12 \frac{h}{w}\right)^{-0.5} \tag{10}$$

The dimension w can be calculated using

$$w = \frac{c}{2f_r} \sqrt{\frac{2}{\epsilon_r + 1}} \tag{11}$$

ϵ_r is the dielectric constant of the chosen antenna substrate material. Lastly, the length extension Δl is calculated using

$$\Delta l = 0.412h \left[\epsilon_{reff} + 0.3 \left(\frac{w}{h} + 0.264 \right) \right] / \left[\epsilon_{reff} - 0.258 \left(\frac{w}{h} + 0.8 \right) \right] \tag{12}$$

Using an FR4 substrate, with dielectric constant $\epsilon_r = 4.3$, equations (8) - (12) are employed to calculate patch sizes to radiate at 2.4 GHz and 5 GHz. To model the dual-band microstrip antenna in the electromagnetic simulator, the 5 GHz patch, which is the smaller of both patches, is embedded within the larger patch, as motivated by [5], thereby creating a microstrip antenna with an inverted U-slot. The antenna is energized using an RF feed line etched unto the antenna ground plane, as inspired by [5]. The dimensions of the groundplane, gaps, and length of the feed line are chosen for modelling convenience. The antenna structure is shown in Figure 1, with the relevant dimensions shown in Table 1. The initial microstrip antenna structure is modelled in the simulator, and a full-wave electromagnetic simulation of the structure is per-

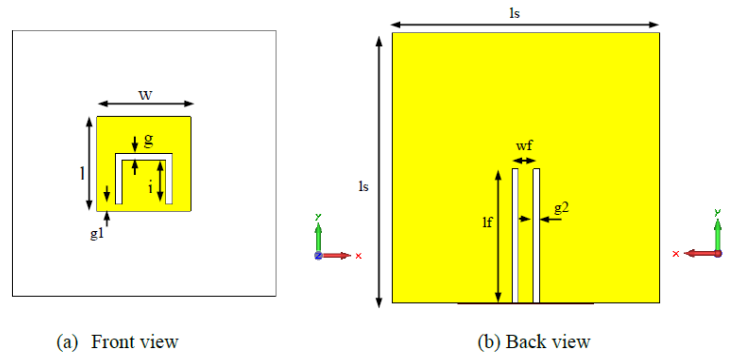


Fig. 1. Antenna structure.

TABLE 1

INITIAL ANTENNA DIMENSIONS

Parameter	Dimension (mm)
ls	40
w	14.24
l	14.24
il	6.65
g	1
g1	1
g2	1
lf	19.9
wf	2.2

3 RESULTS AND DISCUSSION

The full-wave electromagnetic simulation of the antenna structure provides key results of interest that are used to optimize the antenna design. First, the antenna s-parameter and modal significance plots are examined in Figure 2. The modal significance plot is generated using equation (7), where the eigenvalue is derived from the antenna impedance characteristics over the range of frequencies of interest, according to equation (5).

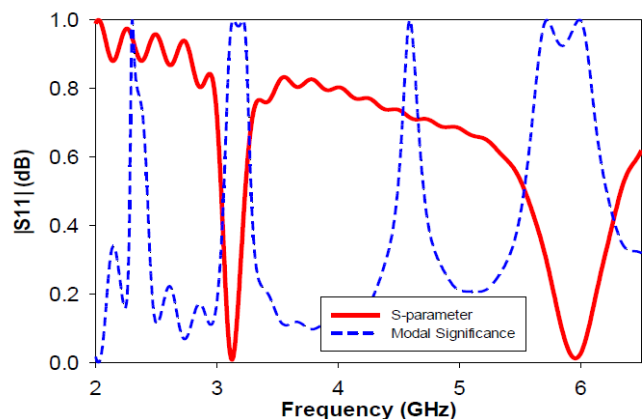


Fig. 2. S-parameter result and modal significance in linear scale
Figure 2 shows that the microstrip antenna has a dual-band

characteristic, with resonances at 3.13 GHz and 5.97 GHz, which however deviate from the required operating frequencies of 2.4 GHz and 5 GHz. The modal significance plot reveals that there are 6 frequencies at which the modal significance is 1. This implies there are 6 frequencies at which the eigenvalue is zero, and the corresponding eigenmodes radiate efficiently [7]. However, it can be observed that only 4 of these eigenmodes are critical to the reflection coefficient performance of the excited antenna. The modes at 3.14 GHz and 3.22 GHz are responsible for the s-parameter resonance at 3.13 GHz, while the modes at 5.72 GHz and 5.99 GHz contribute to the s-parameter resonance at 5.97 GHz.

The surface current distribution on the antenna structure at these 4 modal frequencies are shown in Figure 3. At 3.13 GHz, the surface current is stronger along the l and g dimensions. However, at 3.22 GHz, the surface current is strong along the il and g dimensions. The g dimension is also the area of strongest surface current at 5.72 GHz, while il, g and lf dimensions are significant at 5.99 GHz. It can be deduced that the s-parameter resonance at 3.13 GHz depends on current peaks occurring along the l, g, and il dimensions. On the other hand, the s-parameter resonance at 5.97 GHz is influenced by current peaks along il, g, and lf dimensions.

TABLE 2
OPTIMIZED ANTENNA DIMENSIONS

Parameter	Dimension (mm)
l	17.77
il	8.96
lf	1.45
g	23.59

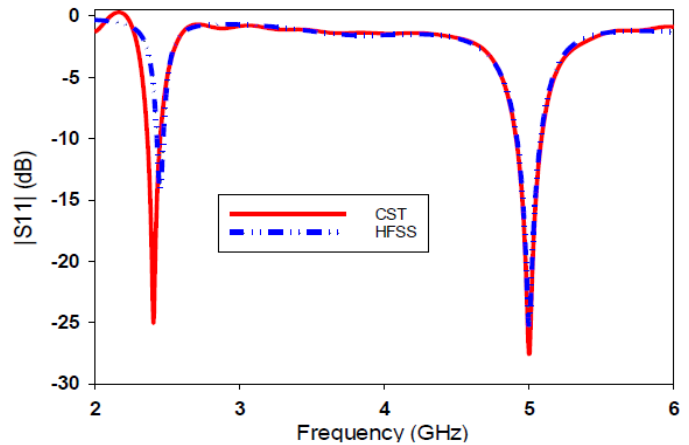


Fig. 4. S-parameter result of optimized antenna

The radiation patterns of the optimized antenna at the two bands of interest are shown in Figure 5. The results show comparable radiation characteristics at both frequencies of interest, with peak gains of 5.23 dBi and 5.97 dBi realized at 2.4 GHz and 5 GHz, respectively. Similarly, good discrimination between cross-and co-polarization patterns are achieved along the main beam direction at both frequencies. As demonstrated in Figure 6, the antenna main lobe direction in the azimuth plane is stable at both resonance frequencies.

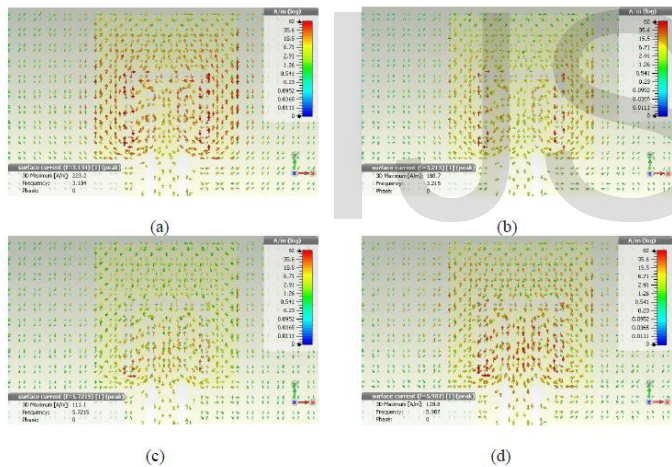


Fig. 3. Antenna surface current distribution at (a) 3.13 GHz, (b) 3.22 GHz, (c) 5.72 GHz and (d) 5.99 GHz

It follows that the resonance performance of the antenna can be altered by adjusting 4 dimensions - l, il, g and lf. Consequently, these 4 dimensions are jointly optimized using the inbuilt optimizer in the electromagnetic solver in order to achieve resonance at 2.4 GHz and 5 GHz. The optimized dimensions are shown in Table 2. As a check, the optimized dimensions are used to model the dual-band antenna in an alternative numerical full-wave electromagnetic simulator, HFSS v.2015©, which is based on the Finite Element Method (FEM). The s-parameter results from both simulators are compared in Figure 4. The close agreement between the results from both simulators validates the choice of parameters for antenna optimization.

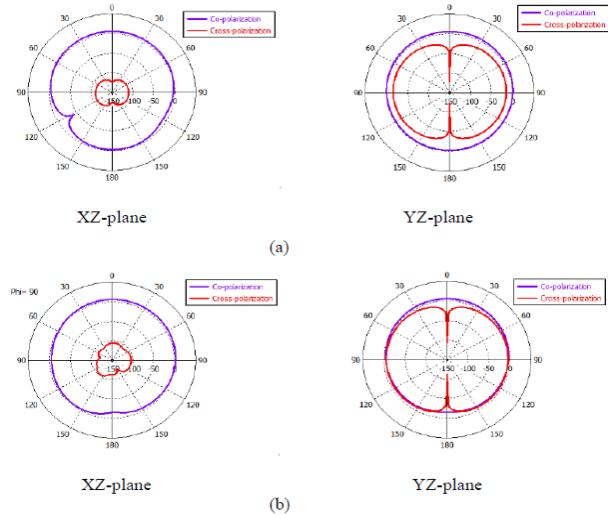


Fig. 5. Antenna polarization at (a) 2.4 GHz and (b) 5 GHz

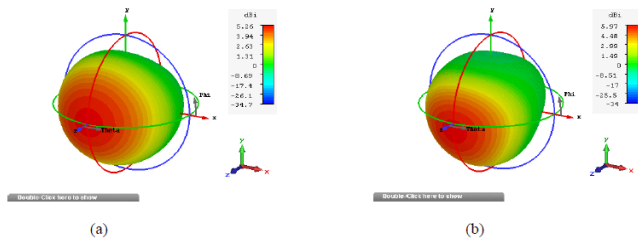


Fig. 6. 3D radiation patterns of optimized antenna at (a) 2.4 GHz, and (b) 5 GHz

4 CONCLUSION

This paper demonstrates the design of a rectangular dual-band microstrip antenna using modal analysis. For the inverted U-slot design, an analysis of the modal significance revealed the frequencies at which resonant eigenmodes occur. Examining the current distribution at these modal frequencies, enabled an appropriate selection of geometric parameters for optimizing the antenna performance. This approach enables the optimization of antenna designs in full-wave electromagnetic simulators without the need for exhaustive parametric studies, even in the absence of automated CMA tools.

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