Shape Synthesis of Multi-mode Dielectric Resonator Antennas Using Characteristic Modes

Binbin Yang [1] and Abdullah Eroglu [1]
[1] Department of Electrical and Computer Engineering
North Carolina A&T State University, Greensboro, NC
byang1@ncat.edu, aeroglu@ncat.edu

Jacob J. Adams [2]
[2] Department of Electrical and Computer Engineering
North Carolina State University, Raleigh, NC, US
jacob.adams@ncsu.edu

Abstract **─** This paper demonstrates a shape synthesis technique for multi-mode dielectric resonator antennas using binary genetic algorithm and characteristic mode analysis. The cost function for the synthesis process is defined from characteristic modal parameters, such as modal quality factors and self-resonance frequencies. Since only modal parameters are involved in the cost function, the shape synthesis process is made independent of feeds. In the paper, we demonstrate the shape synthesis of a DRA with three self-resonant modes at 3 GHz.

Index Terms **─** characteristic modes, dielectric resonator antennas, multi-mode antennas, shape synthesis.

I. INTRODUCTION

Due to their compactness and high radiation efficiency at microwave and millimeter wave frequencies, dielectric resonator antennas (DRAs) have attracted a lot of attention since their initial investigation by Long [1]. However, most of the analysis and designs in literature are limited to DRAs of canonical geometries, such as cylindrical, spherical and rectangular blocks, partially because of the readily available analytical design formulas [2]. While the analytical and empirical design formulas serve the purpose for simple DRA designs, it limits the form factor and the search space of the design. Exploring DRAs of non-canonical geometries could provide new possibilities for DRA miniaturization, multi-mode DRAs and broadband DRAs. With recent advances in the 3D printing of high dielectric constant materials that can be applied to DRA design [3], there are opportunities to investigate novel 3D DRA geometries. Several unconventional DRA designs can be found in [4], [5]. However, the designs are still based on slight modification of the canonical geometry using a combination of intuition and parametric study. A more methodical search algorithm for the desirable DRA geometries would provide a more uniform approach to DRA design and potentially yield performance improvements.

In this paper, we introduce a feed-independent shape synthesis technique for dielectric resonator antennas, as an expansion of our prior work on planar metallic antennas [6]. Though one interesting work on shape synthesis of DRAs has been reported in [7], our approach takes into account of the bandwidth of individual modes in optimization and also has fewer constraints on allowable geometry.

II. SHAPE SYNTHESIS TECHNIQUE AND IMPLEMENTATION

The shape synthesis technique we adopt relies largely upon characteristic mode analysis in order to first create a resonator shape that supports modes with the desired properties. Characteristic mode theory (CMT) [8], a theory for the modal analysis of an antenna/scattering structure, solves the following eigenvalue equation:

$$\mathbf{X}\mathbf{J}_n=\lambda_n\mathbf{R}\mathbf{J}_n, \tag{1}$$

where $\mathbf{X}$ and $\mathbf{R}$ are the imaginary and real parts of the method of moments (MoM) $\mathbf{Z}$ matrix, and λ_n and $\mathbf{J}_n$ are the eigenvalue and eigencurrent of the n-th mode. Depending on the way dielectric objects are modeled, the MoM $\mathbf{Z}$ matrix could be based on surface integral equation (SIE) or volume integral equation (VIE).

As pointed out in [9], the VIE, though computationally heavier than the SIE, avoids the issue of non-physical modes in characteristic mode analysis of DRAs. Furthermore, the eigencurrents calculated from the VIE can be directly used to calculate Q factors from the source formulation as demonstrated in [9]. We therefore choose the VIE for our analysis here.

An important parameter we will use in our optimization is the quality factor of each individual characteristic mode. Once having solved the characteristic eigenvalue equation, the characteristic modal Q factors of DRAs can be calculated from the characteristic modal current and charge distribution, as shown in [9].

A. Shape Synthesis Framework for Multi-mode DRAs

Our shape synthesis of DRAs is based on a binary genetic algorithm, where the binary gene in the chromosome represents the presence or absence of a tetrahedron in the mesh. For the multi-mode DRA synthesis problem studied here, the goal is to search for an antenna geometry with multiple modes resonating at the same frequency, which could be useful for MIMO applications. To facilitate the optimization of broadband self-resonant DRAs, the cost function for the shape synthesis is defined from characteristic modal parameters as:

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$$\text{cost} = \sum_{n=1}^{N} C_n + w_2 V \,, \tag{2}$$

where $C_n = w_1(1 - MS_n) + Q_n$ represents the contribution from the n-th mode. $MS_n=1/|1+j\lambda_n|$ is the characteristic modal significance, and reaches the maximum of 1 at self resonance (λ_n=0). Q_n is the modal Q factor, the minimization of which maximizes the bandwidth. V is the volume of the search geometry normalized to that of the complete geometry, the inclusion of which in the cost function removes unnecessary tetrahedra in the mesh while reducing size and weight. w_1 and w_2 are the weighting coefficients to be selected depending on the problem.

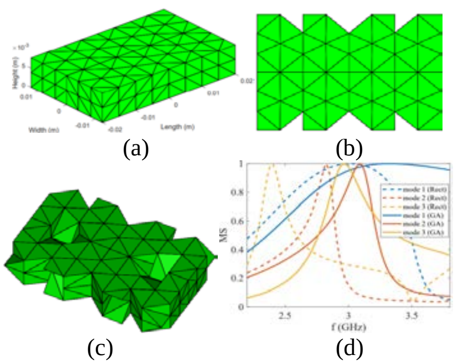

Fig. 1. (a) The complete antenna geometry (Rect), (b) top view, and (c) isometric view of the optimized antenna geometry (GA), (d) the modal significance before (dash) and after (solid) optimization.

Table 1: Comparison of modal significance and modal Q factors before and after optimization at 3 GHz

Modes	MS (Before)	MS (After)	Q (Before)	Q (After)
Mode1	1	0.95	2.2	1.7
Mode2	0.15	0.85	118	8
Mode3	0.29	0.97	11	9.6

III. DESIGN EXAMPLE

Following the shape synthesis technique explained in Section II, we demonstrate the shape synthesis process using an example. The complete structure before optimization has a dimension of 40×25×7.7mm^3, as shown in Fig. 1 (a). The dielectric constant of the material is chosen as 23. The characteristic modal significance for the first three modes of the complete geometry are calculated and shown as dashed lines in Fig. 1 (d). The self-resonant frequencies correspond to the frequencies where MS_n = 1, and we observe from Fig. 1 (d) that the three modes are resonant at 3 GHz, 2.8 GHz and 2.4 GHz respectively.

For demonstration, we optimize the antenna geometry so that three modes are resonant at 3 GHz. The shape synthesis is conducted using a binary genetic algorithm with the cost function in (2) with three modes, a mutation rate of 10%, and the number of generations as 200. The weighting coefficients are selected as w_1= 200, and w_2= 20 after several trials. In order to simplify the optimized geometry and expedite the convergence, we force geometric symmetry in x, y and z dimensions. Figs. 1 (b) and (c) show the top view and isometric view of the final optimized geometry. The modal significance of the first three modes of the optimized geometry is shown as solid lines in Fig. 1 (d). Comparing with the dashed lines, we notice that the resonance frequency of mode 2 has shifted from 2.8 GHz to 3.09 GHz and that of mode 3 has shifted from 2.4 GHz to 2.97 GHz, while the resonance frequency of mode 1 has slightly shifted up (3.3 GHz) as a trade-off. Table 1 compares the modal significance and the modal Q factors of the three modes before and after optimization. It is obvious from the modal significance that all three modes are very close to resonance at 3 GHz after shape synthesis. It is also worth noting that the Q factors of the three modes are optimized as well, with that of mode 2 being significantly reduced from 118 to 8 after optimization.

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