Design of Realistic Phased Array Patch Elements Using a Genetic Algorithm

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Abstract—Presently most wide band array elements are complicated 3-dimensional structures which are difficult and costly to manufacture. Therefore we explore planar patch elements which offer a simplified geometry with potentially reduced weight and cost and are suitable for conformal applications. We use a genetic algorithm to design a patch element in a unit cell of an infinite periodic array and model the feed with the usual δ -gap voltage source. However, since this feed is a non-realizable mathematical concept, we also explore the antenna performance achieved with several realistic feeds. For broadside arrays we obtain a bandwidth $B \approx 4:1$ both with the δ -gap and with the realistic feeds. For arrays with scan angles out to 45° , the initial bandwidth $B \approx 2:1$ with the δ -gap is reduced to $B \approx 1.7:1$ with a differential coaxial feed, whereas the initial bandwidth is maintained with a GA-optimized custom feed. The element profiles range from $0.13 \lambda_L$ to $0.17 \lambda_L$, where λ_L denotes the wavelength at the low end of the operational band.

1. INTRODUCTION

This research concerns the continued development of wide band, wide scan, low profile phased arrays for aircrafts and UAVs. Presently most wide band array elements are complicated 3-dimensional structures which are difficult and costly to manufacture [1-4]. As an alternative, we explore planar patch elements which offer a simplified geometry with potentially reduced weight and cost and are suitable for conformal applications.

Our earlier research has resulted in planar elements with more than octave bandwidth and scan range up to 45° off broadside [5-6]. The approach was inspired by [7] and is based on a genetic algorithm (GA) that optimizes the patch design. The designs assumed an idealized mathematical feed, a δ -gap voltage source, as is common in theoretical antenna studies. Unfortunately, however, such sources do not exist and their replacement by a realistic feed may seriously degrade the array performance. Therefore, in this paper we explore the effects of realistic feeds using two different methods. For a given GA design of a fragmented patch with a δ -gap feed we 1) replace the δ -gap feed with one of several known real feeds, or 2) design a custom feed using the GA.

2. THE APPROACH

Our approach uses a genetic algorithm to design a patch element in a unit cell of an infinite periodic array. Fig. 1 shows top and side views of the unit cell, which includes sub- and superstrates of variable thickness d and relative permittivity ϵ . The patch, which is fed at its center by a δ -gap voltage source, is ‘fragmented’ into a set of pixels that are either conducting or non-conducting. A GA determines the pixel distribution and the sub/superstrates for optimal wide band and wide scan performance by minimizing a cost function F based on reflected power:

$$F = \sum_i \sum_j w_{ij} |R(\Omega_i, f_j)|^4,$$

where R denotes the active reflection coefficient, Ω_i the sample scan angles, f_j the sample frequencies over the design band, and w_{ij} are heuristically chosen weights.

We use the exponent 4 rather than the standard 2 exponent in order to achieve a more uniform, low-level reflection coefficient over the frequency band. For the evaluation of $\Gamma(\Omega_i, f_j)$ we use a highly efficient FDTD code [8], which in one run produces the wide band response of the

Figure 1--Horizontal and vertical cross sections of array unit cell with two sub- and two superstrates of thickness d_i and rel. permittivity ϵ_i . Conducting pixels are shown in red.

array element for any particular scan angle.

It is desirable to work with reasonably high resolution, which, however, must be traded off against computation time. For example, fragmenting the aperture into 20x20 pixels corresponds in principle to a set of 2^{400} different possible geometries. Imposing symmetry among the four quadrants reduces this number to 2^{100} , which still represents an extremely large number of alternatives for the GA to search through. Moreover, we have found that we need to model each pixel by 4x4 fdtd-cells to maintain numerical accuracy. Both the large number of possible geometries and the large number of fdtd-cells contribute to increases in the computation time. Thus, to keep the computation time practical, i.e. less than a week, we normally use only 10x10 pixels.

3. FEED TYPES

The various feed types which we considered are shown in Fig. 2. The δ -gap voltage source with an internal resistance R_i that matches the antenna radiation resistance, (see Fig. 2a), is the most convenient feed for theoretical antenna analysis (and for publishing papers). Unfortunately, it is only an idealized concept and cannot be realized in practice.

The simplest realistic feed is the single coaxial line shown in Fig. 2 b, where the inner and outer conductors connect to the terminals on the patch. The characteristic impedance of the coaxial line again has to match the antenna impedance. However, it represents an 'unbalanced' feed and thus there will be currents flowing on the vertical outer conductor, which will affect the performance.

A better alternative is the differential coaxial feed, (see Fig. 2c), where two coaxial lines excite the patch with signals of equal amplitude and 180° phase difference. This represents a balanced feed and for broadside scan there will be no current (no 'common' mode) induced on the vertical outer conductors. For off-broadside scan, i.e. for asymmetric excitation, both the 'differential' mode and the 'common' mode will be excited. A 180° four-port hybrid as shown in Fig. 2c provides a practical way to generate the differential feed excitation. We chose to leave the Σ -port open-circuited (reflection coeff. = 1) which causes the terminal currents on the opposing side to be equal in magnitude and opposite in phase, regardless of the antenna impedance [9]. In this case, the currents will be balanced, and no common mode current will flow.

Another alternative is the twin-line feed, shown in Fig. 2d. The dimensions of the line have to be chosen such that its characteristic impedance matches that of the array element. The hybrid is again a convenient way to excite the twin-line from an unbalanced, single input.

Finally, in Fig. 2e we show a 'custom' feed, where we let the GA design the feed structure that provides a transition to the patch from a single coaxial input at the ground plane. The basic structure contains two 'shorts' from the patch terminals down to the ground plane, and a center conductor which connects to one of the patch terminals. The widths of these conductors and their spacings are optimized by the GA.

Figure 2 -- Different feed types

4. RESULTS

The unit cell size in all the following examples is 30x30 mm, corresponding to $\lambda/2$ at 5 GHz. The bandwidth is conservatively defined as the frequency band over which the active reflection coefficient $R < -10$ dB.

Patches with δ -Gap Feeds

We first tested the approach on a ‘broadside patch’, i.e. the design of a wideband patch with a δ -gap feed at broadside scan. This resulted in the patch design shown in Fig. 3 and sub- and superstrate dimensions $d_1=14.25$ mm, $\epsilon_1=1$, $d_2=1.5$ mm, $\epsilon_2=3.4$, $d_3=7.5$ mm, $\epsilon_3=2.6$, $d_4=0$. The desired bandwidth is 2.0 – 8.0 GHz in this case and the realized bandwidth is 1.8 – 8.1 GHz. The total profile is $\approx 0.15 \lambda_L$ at the low end of the operational band. Repeated runs with increased desired bandwidth did not result in a correspondingly increased realized bandwidth, which presumably was due to the limited resolution of only 10 pixels.

A second example was a ‘wide scan patch’ with a desired

bandwidth 2.0 – 4.5 GHz and scan out to 45° in both the E- and H-plane. The resultant design is shown Fig. 4, and the sub- and superstrate dimensions are $d_1=17.5$ mm, $\epsilon_1=1.1$, $d_2=1.5$ mm, $\epsilon_2=3.4$, $d_3=d_4=0$. The patch has a realized bandwidth of 2.0 – 4.3 GHz. and a profile $\approx 0.13 \lambda_L$ at the low end of the operational band.

Patches with Real Feeds

We excited the ‘broadside patch’ with a single coaxial line feed, a differential coaxial feed and a twin-line feed. In all cases the feed was matched to the 200 ohm impedance of the patch. The active reflection coefficient corresponding to these three cases is shown in Fig. 5. Not too surprisingly the unbalanced single coaxial feed does not perform well and in this case reduces the initial bandwidth from 1.8 - 8.1 GHz to 3.0 – 5.5 GHz. The other two feeds incur practically no bandwidth reduction.

Similarly we excited the ‘wide scan patch’ with the same set

Figure 3 -- The broadside patch design with δ -gap feed and the active reflection coefficient vs. frequency.

of feeds, the single coaxial line feed, the differential coaxial feed and the twin-line feed, which in this case were matched to the 120 ohm impedance of the patch.

The resultant active reflection coefficient vs. frequency and scan angle are shown in Fig. 6. We note that the bandwidth reduction can be quite dramatic in this case. The single coaxial feed even at broadside scan reduces the bandwidth by about 35% , and considering all three scan angles, the bandwidth is actually reduced to zero.

The two other feeds lead to roughly equal performance with a realized bandwidth of 2.0 – 3.4 GHz, the bandwidth reduction occurring for the E-plane scan. For scan in the H-plane, where the coupling is relatively low, the common mode is not strongly excited and the balanced feeds work well.

Patch with Custom Feed

Finally we show one example of a custom feed which resulted from a GA optimization of the shapes and spacings of the conductors comprising the feed. This patch was somewhat different than the previous wide scan patch. The patch geometry is shown in Fig. 7a, the sub- and superstrate dimensions and permittivities are $d_1=14.25$ mm, $\epsilon_1=1.2$, $d_2=1.5$ mm, $\epsilon_2=3.4$, $d_3=7.5$ mm, $\epsilon_3=1.0$, $d_4=2.25$ mm, $\epsilon_4=6.4$, and the impedance is 200 ohm. With the δ -gap feed the realized bandwidth is 2.1 – 4.4 GHz, see Fig. 7b. With the custom feed as shown in Fig. 8a, the realized bandwidth is 2.0 – 4.0 GHz, see Fig. 8b. This is only a very small bandwidth reduction which, however, is achieved with a rather complicated feed geometry. - The computation time for this case was about 30 days.

Figure 4-- The wide scan patch design with δ -gap feed and the active reflection coefficient vs. frequency (“bs”, “45xz”, and “45yz” denote scan angles of broadside, 45 deg. xz- and 45 deg. yz-plane, resp.).

Figure 5--The broadside patch with different feeds - active reflection coefficient vs. frequency.

Figure 6--The wide scan patch with different feeds - active reflection coefficient vs. frequency (“bs”, “45xz”, and “45yz” denote scan angles of broadside, 45 deg. xz- and 45 deg. yz-plane, resp.).

Figure 7-- Wide scan patch with δ -gap feed and active reflection coefficient vs. frequency.

Figure 8-- Wide scan patch from Fig. 7 with GA designed custom feed and corresponding active reflection coefficient vs. frequency.

5. SUMMARY AND CONCLUSION

For the different patch elements the above results of bandwidth vs. feed type are summarized in Table 1.

For the broadside patch, with a design frequency band 2.0-8.0 GHz, the desired $B = 4:1$ bandwidth is achieved both with the δ -gap feed and with realistic feeds. The profile of this element is $\approx 0.15 \lambda_L$ at the low end of the operational band.

For wide angle scanning arrays, the design of a realistic feed, which avoids a reduction of the desired 2.0-4.5 GHz band, clearly poses a difficult problem. Patch 1 achieves an initial bandwidth $B = 2:1$ with a δ -gap feed which is reduced to $B = 1.7:1$ with a twin-line feed. This element has a profile $\approx 0.13 \lambda_L$ at the low end of the operational band. Patch 2 also has an initial bandwidth $B \approx 2:1$, which is practically maintained with the GA designed custom feed. The profile of this latter element is $\approx 0.17 \lambda_L$ at the low

Table 1-- Bandwidth vs. Feed Type for Different Patch Elements

Feed	Broadside Patch	Wide Scan Patch 1	Wide Scan Patch 2
δ -gap	1.8 – 8.1 GHz	2.2 – 4.3 GHz	2.1 – 4.4 GHz
single coaxial	3.0 – 5.5 GHz	0	---
differential coaxial	1.8 – 5.7 GHz	2.0 – 3.4 GHz	---
twin-line	1.8 – 8.0 GHz	2.1 – 3.4 GHz	---
custom	---	---	2.0 – 4.0 GHz

end of the operational band. Thus it has a somewhat higher profile than the first element; however, it does not require the 4-port hybrid.

The antenna performance of our fragmented patch elements is presently probably limited by our simple geometry and improvements might be obtained with higher resolution, more inter-element coupling control, and additional frequency selective surfaces. An obvious alternative also is to include both the patch and the feed structure in the GA optimization, and such attempts are under way. However, the increased number of free parameters leads to rather long computation times.

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BIOGRAPHY

Hans Steyskal received the degrees Civ. Ing., Tekn. Lic., and Tekn. Dr. in electrical engineering from the Royal Institute of Technology (KTH), Stockholm, Sweden in 1963, 1970 and 1973, respectively. In 1962, he joined the National Defence Research Establishment (FOA), where he investigated microwave radiation and scattering problems. In 1980, he left his position as Chief, Section for Field and Circuit Theory, and moved permanently to the United States. There he has pursued his research interests in electromagnetics, phased array antennas, digital beamforming and array signal processing at the AF Research Laboratory, Antenna Technology Branch, Hanscom AFB, MA, since 2004 as AFRL Senior Scientist for Antennas. In 2007 he retired and works now as an AFRL on-site contractor.

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