Genetically Engineered Miniature Multiband Fractal Antennas

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Overview

• A review of IFS/GA technique developed for optimization of miniature multi-band Fractal Element Antennas (FEA)
• A new challenge in optimizing FEA
• An alternative approach – Matching Network
• Combination of loads and matching network to meet the design objective
Goal

- Goal is to produce antennas that are:
  - Small
  - Efficient
  - Multi-band
Fractal Geometry Based on Iterated Function Systems (IFS)

- Proposed by Michael Barnsley at the Georgia Institute of Technology as a method to generate fractal structures.
- Iterated Function Systems are one type of an affine transformation:
  - Translate
  - Rotate
  - Scale (scaling always results in shrinkage)
- Coordinates of a point are transformed to a new position
- When applied to geometric figures, the figure is translated, rotated and shrunk. However, the original shape is preserved.
Fractal Geometry Based on Iterated Function Systems (IFS)

- An affine transformation \( w \) is given by six numbers
  - \( a, b, c \) and \( d \) perform rotation and scaling
  - \( e \) and \( f \) perform linear translation

\[
\begin{pmatrix}
  a_n & b_n & e_n \\
  c_n & d_n & f_n
\end{pmatrix}
\]

\[
w_n(x,y) = (a_n x + b_n y + e_n, c_n x + d_n y + f_n)
\]
IFS Example - Koch Curve

\[ W(A) = w_1(A) \cup w_2(A) \cup w_3(A) \cup w_4(A) \]

1. \[ w_1(x,y) = \left( \frac{1}{3} x + (0)y + 0, (0)x + \frac{1}{3} y + 0 \right) \]
2. \[ w_2(x,y) = \left( \frac{1}{6} x - \frac{\sqrt{3}}{6} y + \frac{1}{3}, \frac{\sqrt{3}}{6} x + \frac{1}{6} y + 0 \right) \]
3. \[ w_3(x,y) = \left( \frac{1}{6} x + \frac{\sqrt{3}}{6} y + \frac{1}{2}, -\frac{\sqrt{3}}{6} x + \frac{1}{6} y + \frac{\sqrt{3}}{6} \right) \]
4. \[ w_4(x,y) = \left( \frac{1}{3} x + (0)y + \frac{2}{3}, (0)x + \frac{1}{3} y + 0 \right) \]
IFS Example - Koch Curve

Transformation is applied for each iteration to achieve higher levels of fractalization.

Iteration 1 → Iteration 2 → Iteration 3 → Iteration 4
IFS Example - Sierpinski Gasket Variation

<table>
<thead>
<tr>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
<th>f</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.500</td>
<td>0.000</td>
<td>0.000</td>
<td>0.500</td>
<td>0.000</td>
<td>0.000</td>
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<td>0.500</td>
<td>0.000</td>
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<td>0.000</td>
</tr>
<tr>
<td>0.500</td>
<td>0.000</td>
<td>0.000</td>
<td>0.500</td>
<td>0.000</td>
<td>0.500</td>
</tr>
</tbody>
</table>
### IFS Example – Fractal Crystal

<table>
<thead>
<tr>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
<th>f</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.255</td>
<td>0.0</td>
<td>0.0</td>
<td>0.255</td>
<td>0.3726</td>
<td>0.6714</td>
</tr>
<tr>
<td>0.255</td>
<td>0.0</td>
<td>0.0</td>
<td>0.255</td>
<td>0.1146</td>
<td>0.2232</td>
</tr>
<tr>
<td>0.255</td>
<td>0.0</td>
<td>0.0</td>
<td>0.255</td>
<td>0.6306</td>
<td>0.2232</td>
</tr>
<tr>
<td>0.370</td>
<td>-0.642</td>
<td>0.642</td>
<td>0.370</td>
<td>0.6356</td>
<td>-0.0061</td>
</tr>
</tbody>
</table>
### IFS Example - Fractal Tree

<table>
<thead>
<tr>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
<th>f</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.195</td>
<td>-0.488</td>
<td>0.344</td>
<td>0.443</td>
<td>0.4431</td>
<td>0.2452</td>
</tr>
<tr>
<td>0.462</td>
<td>0.414</td>
<td>-0.252</td>
<td>0.361</td>
<td>0.2511</td>
<td>0.5692</td>
</tr>
<tr>
<td>-0.058</td>
<td>-0.07</td>
<td>0.453</td>
<td>-0.111</td>
<td>0.5976</td>
<td>0.0969</td>
</tr>
<tr>
<td>-0.035</td>
<td>0.07</td>
<td>-0.469</td>
<td>-0.022</td>
<td>0.4884</td>
<td>0.5069</td>
</tr>
<tr>
<td>-0.637</td>
<td>0.0</td>
<td>0.0</td>
<td>0.501</td>
<td>0.8562</td>
<td>0.2513</td>
</tr>
</tbody>
</table>
Genetic Algorithms

- Genetic Algorithms are an optimization procedure based on the mechanics of natural selection (i.e., survival of the fittest) and genetics
  - Children inherit traits from their parents and, as a result, resemble them in some fashion. This is achieved in GA via crossover and mutation operators.
  - Survival is based on the fitness of the individual, so that as time progresses there is an evolution in the genetic composition of individuals
  - The Genetic Algorithm can be viewed as a method for distilling good traits from a population of individuals, and recombining them to achieve a goal
- Effective when finding a global minimum in a high-dimension, multimodal function domain
The Genetic Algorithm (GA) program is used in conjunction with an Iterated Function System (IFS) fractal geometry-generating subroutine and a Method of Moments (MoM) code to optimize the radiation characteristics of an antenna (e.g. VSWR, Gain, etc.) for the frequencies of interest.
The following parameters are simultaneously being selected by the GA

- The geometry of the antenna \( (a_n, b_n, c_n, d_n, e_n \text{ and } f_n) \)
- The load component values \( (L_s \text{ and } C_s) \)
- The load locations

\[
\begin{align*}
  w_1(x,y) &= (a_1x + b_1y + e_1, c_1x + d_1y + f_1) \\
  w_2(x,y) &= (a_2x + b_2y + e_2, c_2x + d_2y + f_2) \\
  w_3(x,y) &= (a_3x + b_3y + e_3, c_3x + d_3y + f_3) \\
  w_4(x,y) &= (a_4x + b_4y + e_4, c_4x + d_4y + f_4) \\
  w_5(x,y) &= (a_5x + b_5y + e_5, c_5x + d_5y + f_5)
\end{align*}
\]

Where \( a_n, b_n, c_n, d_n, e_n \text{ and } f_n \) are the parameters to be selected by the GA.
Some Examples of Genetically Engineered Fractal Antennas
Miniaturizing A Dipole Antenna
Length of Antenna = 12 cm

Load Locations: Load1 Element 21
- L1 = 15.81250 nH
- C1 = 0.48490 pF

Load2 Element 06
- L2 = 17.98438 nH
- C2 = 0.79960 pF

<table>
<thead>
<tr>
<th>Frequency</th>
<th>VSWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1225 MHz</td>
<td>1.3383</td>
</tr>
<tr>
<td>1575 MHz</td>
<td>1.2872</td>
</tr>
</tbody>
</table>
Length of Antenna = 11.5 cm

Load Locations:
- Load1 Element 21: $L_1 = 15.53125 \, \text{nH}$, $C_1 = 0.5376 \, \text{pF}$
- Load2 Element 06: $L_2 = 17.95312 \, \text{nH}$, $C_2 = 0.8453 \, \text{pF}$

<table>
<thead>
<tr>
<th>Frequency</th>
<th>VSWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1225 MHz</td>
<td>1.2649</td>
</tr>
<tr>
<td>1575 MHz</td>
<td>1.2266</td>
</tr>
</tbody>
</table>
Length of Antenna = 11.0 cm

Load Locations: Load1 Element 05
L1 = 17.26562 nH  C1 = 0.4708 pF

Load2 Element 04
L2 = 17.89062 nH  C2 = 0.9648 pF

<table>
<thead>
<tr>
<th>Frequency</th>
<th>VSWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1225 MHz</td>
<td>1.0738</td>
</tr>
<tr>
<td>1575 MHz</td>
<td>1.3285</td>
</tr>
</tbody>
</table>
Length of Antenna = 10.5 cm

Load Locations: Load1 Element 22  
L1 = 13.9375 nH  C1 = 0.6414 pF

Load2 Element 04  
L2 = 18.92188 nH  C2 = 0.9050 pF

<table>
<thead>
<tr>
<th>Frequency</th>
<th>VSWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1225 MHz</td>
<td>1.1249</td>
</tr>
<tr>
<td>1575 MHz</td>
<td>1.1205</td>
</tr>
</tbody>
</table>
Length of Antenna = 10.0 cm

Load Locations: Load1 Element 25
L1 = 15.98438 nH  C1 = 0.5746 pF

Load2 Element 23
L2 = 13.39062 nH  C2 = 0.6712 pF

<table>
<thead>
<tr>
<th>Frequency</th>
<th>VSWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1225 MHz</td>
<td>1.1884</td>
</tr>
<tr>
<td>1575 MHz</td>
<td>1.1103</td>
</tr>
</tbody>
</table>
Length of Antenna = 9.5 cm

Load Locations:

Load1 Element 22
L1 = 13.48438 nH  C1 = 0.6941 pF

Load2 Element 25
L2 = 12.09375 nH  C2 = 0.1509 pF

<table>
<thead>
<tr>
<th>Frequency</th>
<th>VSWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1225 MHz</td>
<td>1.0386</td>
</tr>
<tr>
<td>1575 MHz</td>
<td>1.1186</td>
</tr>
</tbody>
</table>
Length of Antenna = 9.0 cm

Load Locations: Load1 Element 25
L1 = 12.04688 nH  C1 = 0.3302 pF

Load2 Element 05
L2 = 15.43750 nH  C2 = 0.6642 pF

<table>
<thead>
<tr>
<th>Frequency</th>
<th>VSWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1225 MHz</td>
<td>1.0392</td>
</tr>
<tr>
<td>1575 MHz</td>
<td>1.1430</td>
</tr>
</tbody>
</table>
Length of Antenna = 8.5 cm

Load Locations:
- Load1 Element 25: L1 = 18.79688 nH, C1 = 0.5570 pF
- Load2 Element 09: L2 = 15.43750 nH, C2 = 0.6853 pF

<table>
<thead>
<tr>
<th>Frequency</th>
<th>VSWR</th>
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<tbody>
<tr>
<td>1225 MHz</td>
<td>1.1235</td>
</tr>
<tr>
<td>1575 MHz</td>
<td>1.0224</td>
</tr>
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</table>
Length of Antenna = 8.0 cm

Load Locations:

<table>
<thead>
<tr>
<th>Load Locations</th>
<th>Load1 Element 04</th>
<th>Load2 Element 04</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>13.42188 nH</td>
<td>L2 = 16.15625 nH</td>
</tr>
<tr>
<td>C1</td>
<td>0.1457 pF</td>
<td>C2 = 0.7644 pF</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frequency</th>
<th>VSWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1225 MHz</td>
<td>1.1432</td>
</tr>
<tr>
<td>1575 MHz</td>
<td>1.0470</td>
</tr>
</tbody>
</table>
Length of Antenna = 7.5 cm

Load Locations:
- Load1 Element 04: \( L_1 = 13.5000 \, \text{nH} \) \( C_1 = 0.3671 \, \text{pF} \)
- Load2 Element 25: \( L_2 = 18.35938 \, \text{nH} \) \( C_2 = 0.8910 \, \text{pF} \)

<table>
<thead>
<tr>
<th>Frequency</th>
<th>VSWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1225 MHz</td>
<td>1.0453</td>
</tr>
<tr>
<td>1575 MHz</td>
<td>1.1628</td>
</tr>
</tbody>
</table>
Length of Antenna = 7.0 cm

Load Locations: Load1 Element 23  L1 = 17.95312 nH  C1 = 0.8119 pF
Load2 Element 19  L2 = 19.50000 nH  C2 = 0.1017 pF

<table>
<thead>
<tr>
<th>Frequency</th>
<th>VSWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1225 MHz</td>
<td>1.3338</td>
</tr>
<tr>
<td>1575 MHz</td>
<td>1.1024</td>
</tr>
</tbody>
</table>
Length of Antenna = 6.5 cm

Load Locations: Load1 Element 22  L1 = 16.10938 nH  C1 = 0.8962 pF
Load2 Element 12  L2 = 13.01562 nH  C2 = 0.2107 pF

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>VSWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1225</td>
<td>1.6677</td>
</tr>
<tr>
<td>1575</td>
<td>1.4982</td>
</tr>
</tbody>
</table>
Length of Antenna = 6.0 cm

Load Locations: Load1 Element 22
L1 = 16.35938 nH  C1 = 0.8962 pF

Load2 Element 09
L2 = 16.12500 nH  C2 = 0.3214 pF

<table>
<thead>
<tr>
<th>Frequency</th>
<th>VSWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1225 MHz</td>
<td>1.6956</td>
</tr>
<tr>
<td>1575 MHz</td>
<td>1.4979</td>
</tr>
</tbody>
</table>
Length of Antenna = 5.5 cm

Load Locations: Load1 Element 22
L1 = 15.86914 nH  C1 = 0.9308 pF

Load2 Element 16
L2 = 12.51172 nH  C2 = 0.5371 pF

<table>
<thead>
<tr>
<th>Frequency</th>
<th>VSWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1225 MHz</td>
<td>1.9413</td>
</tr>
<tr>
<td>1575 MHz</td>
<td>1.7861</td>
</tr>
</tbody>
</table>
Current technology to manufacture the FEA requires the smallest possible L & C values in the loads. Less freedom and therefore potentially more difficulty for the GA to meet the design objectives.
Design Accomplishments

• Able to achieved the same design goal with smaller more practical $L$ and $C$ values by constraining parameters of the GA

Developed New Design Schemes

• Matching network only – an alternative design approach to accomplish the same design objective

• Combination of a matching network together with loads to realize a more flexible design approach
FEA with Small Components
(Design Example)

Load 1:
- \( C_1 = 3.0 \text{ pF} \)
- \( L_1 = 2.7 \text{ nH} \)

Load 2:
- \( C_2 = 3.3 \text{ pF} \)
- \( L_2 = 3.3 \text{ nH} \)
Load Component Sensitivity Study

- Input VSWR goal is 2:1
- Resonate frequency of the loads
  - Load 1: 1.8 GHz
  - Load 2: 1.5 GHz (target 1.575 GHz)
Reduced Load Component Sensitivity Study

- High sensitivity requires very tight tolerances on the loads for proper antenna performance
- Values can change with changes in
  - material lots
  - manufacturing runs
  - temperature
- An effort was made to reduce the sensitivity of the load component values by optimizing for frequencies over a 26 MHz bandwidth centered at 1.575 GHz
Small load component example - continued

Reduced Load Component Sensitivity Study

Sensitivity is minimized as shown for load 2
An Alternative Design Approach
Using A Matching Network

The objective of this effort was to achieve similar results to the loaded fractal antenna, but by using a reactive matching network in place of the loads on the wire.
The GA Simultaneously Optimizes

Fractal Antenna Geometry

Matching Network Topology & Component Values

or

or
Matching Network – continued
(Example)

Fractal Dipole
(with no loads)

Balun

50 Ohm Source

$L_1 = 3.938 \text{ nH}$

$C_1 = 3.646 \text{ pF}$

$L_2 = 15.407 \text{ nH}$
Sensitivity Study of Matching Network

Matching NW L1

Matching NW C2

Matching NW L3
Advantages:

- The fractal antennas could be built (without loads) and measured impedances can be used in the GA to determine the optimal topology and component values for a matching network.

- Circumvents any problems that might be attributed to difference in wire thicknesses or shapes between simulated and measured fractal antennas.

- Allows even greater flexibility in the design of unloaded as well as loaded fractal antennas.
Disadvantages:

- Optimizing with matching network alone requires larger component values
The GA Simultaneously Optimizes
Fractal Antenna Geometry
Load Locations & Component Values
Matching Network Topology & Component Values

Matching Network & Loads
Matching Network & Loads
(Example)

Load values: $L = 3.3 \, nH \quad C = 3.3 \, pF$
Matching Network & Loads
(Example - continued)

Fractal Dipole
(with one load)

Balun

C1

L2

C3

50 Ohm Source

GA Selected Matching Network

C1 = 3.133 pF
L2 = 3.184 nH
C3 = 1.070 pF
Matching Network & Loads

(Example - continued)

Load Values:  \( L = 3.3 \, nH \quad C = 3.3 \, pF \)

Matching Network Values:

\( C_1 = 3.133 \, pF \quad L_2 = 3.184 \, nH \quad C_3 = 1.070 \, pF \)

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>VSWR (goal 2:1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1225.0</td>
<td>1.061111</td>
</tr>
<tr>
<td>1562.0</td>
<td>1.676220</td>
</tr>
<tr>
<td>1565.0</td>
<td>1.510146</td>
</tr>
<tr>
<td>1575.0</td>
<td>1.106058</td>
</tr>
<tr>
<td>1580.0</td>
<td>1.147770</td>
</tr>
<tr>
<td>1585.0</td>
<td>1.332390</td>
</tr>
<tr>
<td>1588.0</td>
<td>1.463225</td>
</tr>
</tbody>
</table>
Load Sensitivity Study

Graphs showing the variation of VSWR with L (in nH) and C (in pF) for two different frequencies: 1.225 GHz and 1.575 GHz.
Matching Network Sensitivity Study

MNC1

VSWR vs. pF

MNL2

VSWR vs. nH

MNC3

VSWR vs. pF
Summary

A powerful new tool has been developed for the design of miniature multi-band antennas with practical component values for loads and matching networks. The new technique allows the GA to simultaneously optimize:

- The fractal antenna geometry
- Load component values and locations
- Matching network topology and component values