Magnetically Tuned CRLH CPW Zeroth Order Antenna

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Abstract – This paper presents the results in frequency tuning of a CPW antenna based on CRLH (Composite Right/Left-Handed) transmission lines. In order to be tuned, the antenna was made on a ferrite substrate. The tuning is obtained by magnetically biasing this ferrite substrate with a magnetic biasing field variable between 0 T and 0.26 T. Data obtained by simulation with a suitable microwave software indicate a frequency shift of 530 MHz at a working frequency of 12.88 GHz, in very good agreement with the experimental results showing a frequency shift of 450 MHz.

I. INTRODUCTION

A possibility to obtain transmission media having metamaterial (MM) characteristics is to develop particular artificial transmission lines. If the artificial transmission line is realized by using cascaded cells of interdigital capacitors and parallel connected short-ended microstrip line inductors, CRLH (Composite Right/Left-Handed) transmission lines are obtained [1]. The CRLH cell opened a new class of circuit topology for many devices such as coupled-line directional couplers [2], filters and resonators, [3] – [5] and various types of antennas [6] – [13]. Concerning the domain of antennas made on the basis of MMs, a lot of contributions were produced, some of the more recent being [10] – [13].

A lot of research efforts were made in order to obtain CRLH devices with frequency tuning properties. In this respect, electronically controlled transmission lines [14], voltage tunable split-ring resonators [15] and various antennas [16], [17] were reported.

A promising class of microwave and millimeter wave CRLH components consists of devices supported on magnetically biased ferrite. In literature there are very few contributions concerning this class of devices. Recently, [17], authors compared four related CRLH leaky-wave antennas where the CRLH structure dispersion is controlled by an applied magnetic field.

In this contribution we present a CRLH CPW zeroth order antenna having a magnetically polarized ferrite as supporting substrate. This antenna structure on silicon was previously reported in [13].

II. ANTENNA MODELING

The antenna is an array of three CRLH cells, each one having a T circuit topology consisting of two series connected CPW interdigital capacitors and two parallel connected short-ended CPW transmission lines.

The equivalent circuit of one CRLH cell is presented in Fig.1 (a), where $2C_L$ and $L_R/2$ are the equivalent capacitance and the equivalent inductance of the series capacitor, while $C_R$ and $L_L$ are the equivalent parallel capacitance and the equivalent parallel inductance of the two CPW transmission lines. The parallel capacitance $C_R$ includes the equivalent capacitance of the short-ended CPWs as well as the equivalent parallel capacitance of the interdigital capacitors. It is important to point out that $L_R/2$ and $C_R$ are strongly related to the $2C_L$ and $L_L$ values. In Fig. 1 (b) a detail of the area around the junction between the CPW interdigital series capacitors and the CPW inductive stubs to the ground are shown.

For an open-ended CRLH antenna, the frequency of the zeroth-order resonance is:

$$f_{sh} = \frac{1}{2\pi\sqrt{L_L C_R}}$$  (1)
which is the parallel resonance due to the two CPW short-ended transmission lines.

The capacitor was designed imposing the technological resolution of 10 μm, the length of the capacitor fingers (which has to be much smaller compared to the operating wavelengths) of 0.5 mm for the internal capacitors and of 1 mm for the capacitors at the ends of the antenna. The intended resonance frequency was $f_{sh} = 13$ GHz, but a 12.88 GHz resonance frequency resulted after the final dimensioning of the components.

The layout of the CRLH cell was designed and then optimized using the IE3D – Zeland software and the following results were obtained:

- The CPW inductor line length – 1.5 mm;
- The width of the CPW central conductor – 100 μm;
- The width of the CPW slot – 10 μm;
- The length of the interdigital capacitor at the end of antenna – 1 mm and 0.5 mm for the internal interdigital capacitor;
- The width of the metallic finger of the interdigital capacitor – 10 μm;
- The space between two fingers of the interdigital capacitor – 10 μm; the space between the interdigital capacitor and the ground planes of the CPW structure – 100 μm;
- The number of the metallic fingers of the interdigital capacitor is equal to 10.

For this layout, the elements of the CRLH equivalent circuit (see Fig. 1) were computed for the interdigital capacitor and for the short-ended inductive CPW lines: $L_L = 0.55 \text{nH}$, $C_L = 0.18 \text{pF}$, $L_R = 0.3 \text{nH}$ and $C_R = 0.23 \text{pF}$.

The zeroth-order resonating antenna consists of three CRLH cells, each one having the above dimensions. An input CPW line of 4.5 mm length was used for the connection to the measurement system. The complete electromagnetic analysis of the antenna layout was carried out by the IE3D – Zeland software.

A polycrystalline garnet having the saturation magnetization $4\pi M_s = 550 \text{ G}$, permittivity $\varepsilon = 13.5$ and resonance linewidth $\Delta H = 16.8 \text{ kA/m}$ was used as substrate.

The thickness of the ferrite substrate was 0.5 mm and the surface to be metallized was mirror polished. The antenna layout was designed for an external applied field $H_{appl} = 0 \text{T}$, namely, for the ferrite substrate in unmagnetized state.

At the application of a biasing magnetic field ($H_{appl}$) normally on the ferrite substrate, the permeability changes its values from unpolarized state. The effective permeability $\mu_{eff}$ of the magnetically biased ferrite substrate was computed with a suitable software using the relations [2] ... [8], cf. [18].

$$\mu_{eff} = 1 + \frac{\omega_M^2}{\omega_L^2 - \omega^2} \left( 1 - \frac{\alpha^2}{\alpha^2} \right)$$

where:

$$\omega = \gamma M_s$$

$$\gamma = \frac{g\gamma}{\Delta H/2H_r}$$

For the geometric shape of the ferrite substrate – a thin wafer having the thickness much smaller than the other two dimensions with the biasing magnetic field applied normally on its surface – the internal magnetic field ($H_i$) is deduced as:

$$H_i = H_{appl} - M_s$$

The effective permeability ($\mu_{eff}$) of the ferrite substrate varies when the applied magnetic field changes from $H_{appl} = 0 \text{T}$ to $H_{appl} = 0.26 \text{T}$ and the graph of this variation is shown in Fig. 2. It must be noted that for this domain of the applied field the antenna structure works under the gyromagnetic resonance.

![Fig. 2. Effective permeability vs. applied magnetic field](image-url)
When the ferrite substrate is magnetically biased, the effective permeability decreases (see Fig. 2) from $\mu_{\text{eff}} = 1$ for $H_{\text{appl}} = 0$ T to $\mu_{\text{eff}} = 0.921$ for $H_{\text{appl}} = 0.26$ T. These values for $\mu_{\text{eff}}$ were used in the IE3D software. The modeling of the antenna frequency and return-loss was carried out for four values of the applied magnetic field. The return-loss and the frequency for each value of the magnetic biasing field are specified in Table 1 and are shown in graphs in Fig. 3 - (a)…(d).

A higher order resonance frequency can be observed in Fig. 3 (a), corresponding to the series resonance of the first interdigital capacitor.

### Table 1

<table>
<thead>
<tr>
<th>Applied magnetic field (T)</th>
<th>Effective permeability ($\mu_{\text{eff}}$)</th>
<th>Frequency (GHz)</th>
<th>Return loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>12.88</td>
<td>-28</td>
</tr>
<tr>
<td>0.055</td>
<td>0.986</td>
<td>12.96</td>
<td>-20.26</td>
</tr>
<tr>
<td>0.18</td>
<td>0.951</td>
<td>13.20</td>
<td>-22.30</td>
</tr>
<tr>
<td>0.26</td>
<td>0.921</td>
<td>13.41</td>
<td>-17.70</td>
</tr>
</tbody>
</table>

The zeroth-order resonance frequency calculated in the absence of the magnetic biasing field was found as 12.88 GHz with a return losses level of 28 dB – see Fig. 3 - (a). When applying the biasing magnetic field, the calculated frequency for the antenna structures ranges from 12.88 GHz for $H_{\text{appl}} = 0$ T to 13.41 GHz for $H_{\text{appl}} = 0.26$ T. Also, the calculated reflection losses changes from 28 dB at $H_{\text{appl}} = 0$ T to approx. 17.7 dB for $H_{\text{appl}} = 0.26$ T. Therefore a very good impedance matching is obtained in the operating frequency range.

### III. EXPERIMENTAL RESULTS

The technological process for the antenna consists of a one mask positive photolithography process. A 500Å Cr layer followed by 0.6 μm Au were evaporated on the mirror polished side of the ferrite wafer. After that, the metallic pattern was obtained by wet etching. A microscope photo showing the configuration of the interdigitated capacitors and part of inductor lines is shown in Fig. 4. The area occupied by the antenna active area is 3.9 mm × 3.4 mm, having a size reduction of ~30%, compared with a $\lambda/2$ patch antenna.

![Fig. 4. Microscope photo of the fabricated antenna.](image)
The individual antenna structures were obtained by cutting the ferrite wafer. Each antenna structure was mounted on a suitable test fixture (see Fig. 5) in a measurement system shown in Fig. 6, able to measure microwave frequency and reflexion loss while applying a biasing static magnetic field normally on the ferrite antenna substrate. The dc magnetic field is produced by an electromagnet.

The acquired experimental results concerning the measured resonating frequencies and return loss (RL) of two antenna structures are shown in Table II and in Figs. 7 and 8.

The data from Table II was used to obtain curves showing the frequency variation and return loss variation as function of the applied magnetic field for the two antenna structures – Fig. 7 and Fig. 8.

<table>
<thead>
<tr>
<th>Happl. (T)</th>
<th>Antenna structure 1</th>
<th>Antenna structure 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Freq. (GHz)</td>
<td>RL (-dB)</td>
</tr>
<tr>
<td>0</td>
<td>13.35</td>
<td>18</td>
</tr>
<tr>
<td>0.02</td>
<td>13.35</td>
<td>18</td>
</tr>
<tr>
<td>0.04</td>
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<td>0.06</td>
<td>13.38</td>
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</tr>
<tr>
<td>0.08</td>
<td>13.4</td>
<td>19</td>
</tr>
<tr>
<td>0.10</td>
<td>13.41</td>
<td>19</td>
</tr>
<tr>
<td>0.12</td>
<td>13.44</td>
<td>19</td>
</tr>
<tr>
<td>0.16</td>
<td>13.49</td>
<td>19</td>
</tr>
<tr>
<td>0.18</td>
<td>13.51</td>
<td>18</td>
</tr>
<tr>
<td>0.20</td>
<td>13.58</td>
<td>17</td>
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<tr>
<td>0.22</td>
<td>13.63</td>
<td>17</td>
</tr>
<tr>
<td>0.24</td>
<td>13.70</td>
<td>16</td>
</tr>
<tr>
<td>0.26</td>
<td>13.8</td>
<td>14</td>
</tr>
</tbody>
</table>

It can be observed that for a magnetic biasing field less than 0.055 T, the resonating frequencies of the two antennas were 13.57 GHz and 13.35 GHz, respectively, slightly higher than the simulated results (see Table I). If the applied magnetic field remains under the value of the saturation magnetization, (550 Gs), the working frequencies maintain their initial values. At higher values of Happl, the resonance frequencies of the antennas tend to increase, as it may be seen in Table II and in Fig. 7 and Fig. 8. The total measured frequency shift was 400 MHz for the first antenna and 450 MHz for the second one, when the biasing magnetic field was varied from Happl = 0 T to Happl = 0.26 T. This frequency shift fits very well with the calculated values. The difference between the calculated and measured resonance frequency at
The measured return losses of the two antenna structures are also presented in Fig. 7 and Fig. 8. It should be observed that the experimental values for the return loss and the simulated values given in Table I are in very good agreement.

IV. CONCLUSIONS

In this contribution, we present a CRLH CPW zeroth-order antenna having a magnetically polarized ferrite as supporting substrate. The antenna was analyzed using a full-wave electromagnetic analysis software and two structures were manufactured on a ferrite substrate and measured. The experimental data shows a frequency shift of 400 MHz for one of the antenna structures and 450 MHz for the other one, due to the variation of the effective permeability of the ferrite substrate. The measured frequency shifts are consistent with the calculated values for a particular magnetic biasing field, the increase of the return loss values being also consistent with the calculated values. This work demonstrates the possibility to tune a CRLH antenna made on a ferrite substrate by varying the biasing magnetic field.

The interesting results obtained entitle us to consider the manufacturing and characterization of other CRLH devices on this type of ferrite substrate.

REFERENCES


