Miniaturized 3-Bit Frequency-Reconfigurable Monopole Antenna with a Meander-Line

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Introduction: With the rapid development of modern wireless communication systems, RF front-ends are required to operate at multiple frequency bands, and the number of integrated antenna and total dimensions is highly increased. To solve the problems, reconfigurable antennas have been extensively studied recently.

Reconfigurable antennas can be classified into three types, namely, frequency-reconfigurable antennas (FRAs) [1]-[10], polarization-reconfigurable antennas [11], and radiation pattern reconfigurable antennas [12]. Among them, FRAs have attracted substantial attention and been intensively studied. The frequency of an FRA can be continuously tuned using varactors [1]-[5] or discretely switched using RF-switches [6]-[10]. Frequency
reconfigurability has been achieved on various types of antennas, such as microstrip patch antennas (MSAs) [1], [2], [9], dipole antennas [3], patch-slot antennas (PSAs) [6], microstrip monopole antennas (MMAs) [7], microstrip slot antenna (MSA) [8], and planar inverted-F antennas (PIFAs) [10]. Majority of FRAs tune/switch the resonant frequencies by reconfiguring the current flow path on the antenna or reshaping the antenna structure, changing the equivalent electrical lengths of antennas in addition.

Nonetheless, many of these published FRAs fail to take miniaturization into account, which is critical especially when FRAs are used in handheld devices. Typically, antenna miniaturization is accomplished by folding the radiation branch of the antenna [13], [14], by selecting an antenna patch loaded with a specialized shape [15] or a shorting wall [16], and by introducing metasurfaces [17] or metamaterial structures [18]. The most common method of antenna miniaturization is to use a meander line. In [14], a miniaturized monopole chip antenna with meander lines on the first and third layers is presented, greatly reducing the antenna’s size at lower and upper bands.

Furthermore, many published FRAs load too many switches while only providing a limited number of operational states. Fortunately, binary reconfiguration can successfully resolve this problem by realizing $2^N$ switchable states with $N$ switches. A 3-bit binary reconfigurable PIFA with eight independent states covering a working frequency range from 1.52 GHz to 2.25 GHz is developed by using three MEMS switches in [10]. The presented FRA is miniaturized by the meander line in [7], and only three states are achieved using two diodes.

In this study, a miniature 3-bit frequency-reconfiguring monopole antenna with a meander-line is proposed. It employs three switches to achieve $2^3$ states, which is the maximum number of states. The structure can be extended for achieving binary FRA with larger number of bits.

![Antenna Diagram](image)

**Fig. 1** Geometry of the proposed antenna. $L_0 = 5$ mm, $L_1 = 6$ mm, $L_2 = 12.4$ mm, $L_3 = 2.8$ mm, $L_4 = 6$ mm, $L_5 = 4.4$ mm, $L_6 = 8.6$ mm, $W_0 = 1.8$ mm, $W_1 = 1.6$ mm, $W_2 = 0.3$ mm, $S_1 = 10.3$ mm, $S_2 = 6.2$ mm, $S_3 = 9.8$ mm.
Fig. 2. Surface current distributions for state 001 (a), state 100 (b), state 101 (c), and state 111 (d).

Antenna Configuration and Miniaturization Design:

Fig. 1 shows a miniaturized binary frequency-reconfigurable meander-line antenna. The main transmission line of the antenna is folded three times at different locations. Three meanders have uniform width.

As shown in Fig. 1, three PIN diode switches are introduced at the meander of the main transmission line, and short narrow strips extended from the meanders are used to place PIN diodes. By switching on the PIN diode switch, the relevant parts of the bending structure with different lengths are bypassed from the antenna structure. The current flows directly from the PIN switch without passing through the bypassed transmission line section, resulting in a shorter actual path length of the current. Consequently, the operating frequency of the antenna increases. On the contrary, the corresponding parts are connected to the antenna structure by turning off the switch. For example, when the PIN diode D1 is turned on, the BP1 section is bypassed, and the current passes directly through the switch D1 without going through BP1. As a result, the actual path length of the current is shortened, and the frequency of the antenna is correspondingly increased. Different settings of the on/off status of D1, D2, and D3 result in changes in the effective length of the antenna, which can achieve $2^3$ different operating frequencies and realize frequency reconfigurability.

As for the biasing circuit, $C_1$, $C_2$, $C_3$, $C_4$, and $C_5$ achieve DC-blocking, dividing the antenna into multiple transmission line segments with different DC voltages. $I_{n1}$ and $I_{n2}$, as RC chokes, are connected to ground via holes and achieve DC grounding as one end of the PIN diodes $D_1$, $D_2$, and $D_3$. The three control voltages, $V_1$, $V_2$, and $V_3$ are respectively connected to the other end of $D_1$, $D_2$, and $D_3$ via inductors $I_{n3}$, $I_{n4}$, and $I_{n5}$.
3-Bit Frequency-Reconfiguration Design: The influence of the bypassed part on the electrical length of the antenna is assumed to be negligible, and the current is uniformly distributed in the bending line. Switches \( D_1, D_2, \) and \( D_3 \) are assigned to the centers of meanders 1, 2, and 3, with different positions in the x-axis direction. To achieve binary frequency reconfiguration, the length of the bypassed transmission line \( S_1, S_2, \) and \( S_3 \) are proposed to satisfy: \( S_1 > S_2 > S_3 \). By operating the three switches as shown in Table I, eight independent antenna working states can be obtained, with "1" representing "on" and "0" representing "off" (i.e., achieving the 3-bit frequency reconfiguration).

Fig. 2 depicts the simulated surface current distribution at various resonant frequencies. When one of the switches is turned on, a portion of the corresponding meander is bypassed, resulting in a new structure that can be equivalent to an open stub, as shown in the figure. As a result, the current path on the meander line is reconfigured, as indicated by the red curves, avoiding the bypassed part and flowing directly through the p-i-n diode. Therefore, the equivalent electrical length of the meander is reduced. When the switch is turned off, the related part of the meander is incorporated into the meander line, increasing the antenna’s electric length.

In Fig. 2(a), the current density of the bypassed part of meander three is significantly reduced by turning on \( D_3 \), reducing the corresponding electrical length of the antenna. In addition, the resonant frequency shifts to a higher band compared with the condition when \( D_3 \) is turned off.

When either of the switches, as shown in Figs. 2(b) and 2(c), are turned on, the longer the shortened current path, the shorter the equivalent electrical length of the meander line, and the higher the working frequency of the antenna are obtained.

Finally, in Fig. 2(d), the highest working frequency is attained at state 111 because the shortest current path on the meander line and the smallest equivalent electrical length of the antenna, which resulted from all three switches being turned on.

The electrical length obviously decreases sequentially from state 000 to state 111, resulting in a gradual increase in the resonant frequency of the antenna. Therefore, the frequency range of the roughly reconfigurable can be first determined based on \( f_H \) and \( f_L \), followed by the resonance frequencies of the eight different
operating states. Owing to miniaturization, the range of reconfigurable frequencies is limited by the size of the antenna. Thus, the operating frequency bands of each state must be optimized to ensure that they are clear and evenly distributed within a finite frequency range and minimize overlap as much as possible. All the simulation and parameter optimization of the antenna proposed in this study are realized by computer simulation technology (CST) software.

The antenna proposed in this study is designed to operate in the frequency range of 1.04–1.51 GHz with a bandwidth from 80 MHz to 150 MHz. In the practical design of the reconfigurable antenna, the intermediate dielectric layer employs Rogers RO4003C substrate, with a relative dielectric constant of 3.38 and a thickness of 0.813 mm. In addition, the RF PIN diodes from Skyworks with a PIN of SMP1331-079LF are used [19], and the diode is equivalent to a resistance of 1.7 Ω and a capacitance of 0.18 pF at the on and off states in simulation, respectively.

The optimized parameters obtained from the simulation are: $L_0 = 5$ mm, $L_1 = 6$ mm, $L_2 = 2.8$ mm, $L_3 = 6$ mm, $L_4 = 4.4$ mm, $L_5 = 8.6$ mm, $W_0 = 1.8$ mm, $W_1 = 1.6$ mm, $W_2 = 0.3$ mm, $S_1 = 10.3$ mm, $S_2 = 6.2$ mm, and $S_3 = 9.8$ mm. The values of the bias inductors $I_{n1}$, $I_{n2}$, $I_{n3}$, $I_{n4}$, and $I_{n5}$ are 180 nH. The values of the DC blocking capacitors $C_1$, $C_2$, $C_3$, $C_4$, and $C_5$ are 100 pF.

**Table I:** Conditions of diodes in different states.

<table>
<thead>
<tr>
<th>States</th>
<th>Diodes</th>
<th>000</th>
<th>001</th>
<th>010</th>
<th>011</th>
<th>100</th>
<th>101</th>
<th>110</th>
<th>111</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_1$</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>On</td>
<td>On</td>
<td>On</td>
<td>On</td>
</tr>
<tr>
<td>$D_2$</td>
<td>Off</td>
<td>Off</td>
<td>Off</td>
<td>On</td>
<td>On</td>
<td>Off</td>
<td>Off</td>
<td>On</td>
<td>On</td>
</tr>
<tr>
<td>$D_3$</td>
<td>Off</td>
<td>On</td>
<td>Off</td>
<td>On</td>
<td>Off</td>
<td>On</td>
<td>Off</td>
<td>On</td>
<td>On</td>
</tr>
</tbody>
</table>

The results show that $S_3$ is larger than $S_2$ after optimization. This is because the initial assumption is that the current distribution along the
meander line is uniform, but the contribution of each bypassed section on frequency reconfiguration is not proportional to the length. As a result, the current distribution along the meander line is varying, and S3 becomes larger than S2. Aside from the phenomenon of increasing S3, Fig. 2 shows that the current path of each state is fundamentally the same as the equivalent structure of the corresponding state, and the bypassed sections are with no current.

Fig. 3 depicts the ultimate simulated S11 results at various states of the proposed antenna. The eight states are completely self-contained and have good impedance-matching performance over a frequency range of 1.14–1.6 GHz. Within the operating frequency band, the return loss, S11, is less than 10 dB. At the lowest working frequency (1.14 GHz), the size of the antenna is reduced to 0.19 λ0 × 0.08 λ0.

Table II. Simulated and measured resonance frequencies and operating bandwidths.

<table>
<thead>
<tr>
<th>State</th>
<th>Sim. freq</th>
<th>Mea.freq</th>
<th>Sim.BW</th>
<th>Mea.BW</th>
</tr>
</thead>
<tbody>
<tr>
<td>000</td>
<td>1.16GHz</td>
<td>1.09GHz</td>
<td>40MHz</td>
<td>90MHz</td>
</tr>
<tr>
<td>001</td>
<td>1.20GHz</td>
<td>1.17GHz</td>
<td>50MHz</td>
<td>100MHz</td>
</tr>
<tr>
<td>010</td>
<td>1.23GHz</td>
<td>1.23GHz</td>
<td>60MHz</td>
<td>90MHz</td>
</tr>
<tr>
<td>011</td>
<td>1.28GHz</td>
<td>1.27GHz</td>
<td>60MHz</td>
<td>110MHz</td>
</tr>
<tr>
<td>100</td>
<td>1.27GHz</td>
<td>1.29GHz</td>
<td>65MHz</td>
<td>80MHz</td>
</tr>
<tr>
<td>101</td>
<td>1.35GHz</td>
<td>1.33GHz</td>
<td>80MHz</td>
<td>100MHz</td>
</tr>
<tr>
<td>110</td>
<td>1.40GHz</td>
<td>1.39GHz</td>
<td>90MHz</td>
<td>110MHz</td>
</tr>
<tr>
<td>111</td>
<td>1.53GHz</td>
<td>1.44GHz</td>
<td>140MHz</td>
<td>150MHz</td>
</tr>
</tbody>
</table>

Fig. 5. Photograph of the proposed 3-bit FRA.
**Results and discussion:** The measured results of the reflection coefficient and the photograph of the antenna prototype are given in Fig. 4 and Fig. 5. The S11 results are measured with an Agilent N5230A vector network analyzer. Eight independent states are observed with the operating frequency switched from 1.04 GHz to 1.51 GHz. Good impedance matching and low return loss are obtained for each state, and the simulated and measured working frequency and bandwidth at each state are compared in Table II. Except for a small frequency shift of approximately 74 MHz on average for each state, agreement between the simulation and the measurement results is good. The measured bandwidths are larger than the simulated ones, and this is possibly caused by the resistive loading of the biasing components and switches in practical designs. Furthermore, Fig. 4(a) shows a few unexpected perturbations on the S11 curves caused by the parasitic effect of biasing lumped elements. Fig. 5 gives a photograph of the fabricated prototype antenna.

**Fig. 6.** Simulated (dashed line) and measured (solid line) radiation patterns at resonant frequencies of state 001 and state 111. (a) E-plane; (b) H-plane.

**TABLE III.** Comparison of several frequency reconfigurable antennas

<table>
<thead>
<tr>
<th>Ref</th>
<th>Type</th>
<th>Size</th>
<th>Freq (GHz)</th>
<th>No. PIN</th>
<th>No. states</th>
<th>Binary reconfigurable</th>
<th>Peak gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1]</td>
<td>MPA</td>
<td>0.44×0.44</td>
<td>1.64-2.12</td>
<td>8</td>
<td>5</td>
<td>No</td>
<td>6.0</td>
</tr>
<tr>
<td>[6]</td>
<td>MPSA</td>
<td>0.13×0.21</td>
<td>1.98-3.59</td>
<td>5</td>
<td>9</td>
<td>No</td>
<td>4.8</td>
</tr>
<tr>
<td>[7]</td>
<td>MMA</td>
<td>0.04×0.01</td>
<td>0.72-2.4</td>
<td>2</td>
<td>3</td>
<td>Yes</td>
<td>7.6</td>
</tr>
<tr>
<td>[8]</td>
<td>MSA</td>
<td>0.52×0.48</td>
<td>2.2-4.75</td>
<td>5</td>
<td>6</td>
<td>No</td>
<td>4.1</td>
</tr>
<tr>
<td>This work</td>
<td>MMA</td>
<td>0.17×0.07</td>
<td>1.04-1.51</td>
<td>3</td>
<td>8</td>
<td>Yes</td>
<td>1.59</td>
</tr>
</tbody>
</table>

In the comparison in Table III, the antenna proposed in this study uses three switches to achieve $2^3$ states,
which is the maximum number of reconfigurable states. Compared with previous FRAs, this antenna has a smaller size and achieves more states using fewer switches.

In far-field situation, the proposed antenna aims to maintain bidirectional radiation characteristics in the E-plane (yz-plane) and nearly omnidirectional pattern in the H-plane (xz-plane) for all the eight states, which is in accordance with the far-field patterns of typical printed MMA. This work is tested in an anechoic chamber. Fig. 6 shows the simulated and measured far-field results at state 111, where radiation patterns are most possibly changed because of the dc supplies for the three switches. The simulated far-field results still agree well with the measured output. The simulated gain for all states varies from 1.11 dBi to 1.59 dBi, where the peak gain is obtained at state 000 because all switches are turned off, and the radiation efficiency is larger than 84%. However, the measured peak gain is 0.5 dBi because the p-i-n diodes and many lumped elements introduce some losses.

**Conclusion:** A 3-bit frequency reconfigurable meander-line MMA is proposed. The antenna has $2^3 = 8$ independent narrow band states. The number of states is optimally large in terms of the number of switches used because of the antenna’s binary reconfigurability. The measured results agree well with the simulated ones, and good impedance matching characteristics and acceptable bandwidth are achieved on each state, covering a considerable frequency range from 1.01 GHz to 1.54 GHz. This antenna has similar far-field radiation characteristics as the traditional MMA and features in immensely miniaturized size.

**Acknowledgement:**

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**References**

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