Frequency Reconfigurable Spirograph Planar Monopole Antenna (SPMA)

Jennifer Taylor Rayno and Satish K. Sharma
Electrical and Computer Engineering, San Diego State University
5500 Campanile Drive, San Diego, CA 92182 USA
jennifer_heather@yahoo.com, ssharma@mail.sdsu.edu

1. Introduction

Today's communication systems demand both increased performance and reduced size. A frequency reconfigurable antenna provides the capability for the antenna to operate in only the desired frequency range while rejecting neighboring ones. This reduces interference which will consequently increase S/N ratio, thus channel capacity or power efficiency. An antenna which covers multiple bands provides an aperture which can be used for multiple applications, thus a reusable aperture, or the entire bandwidth can be used simultaneously to provide high data rate. Also by consolidating the number of antennas required, the overall size of the system is decreased. If the antenna dimension is small enough such that it can be used as a scanning array element (typically $< 0.6\lambda$ at the highest frequency of operation), high gain and/or beam scanning applications can be accommodated [1], which further increases performance. A reusable aperture, high data rate capability, and beam scanning capability create a multi-purpose system, which decreases the number of antennas required to cover various applications while increasing system capability.

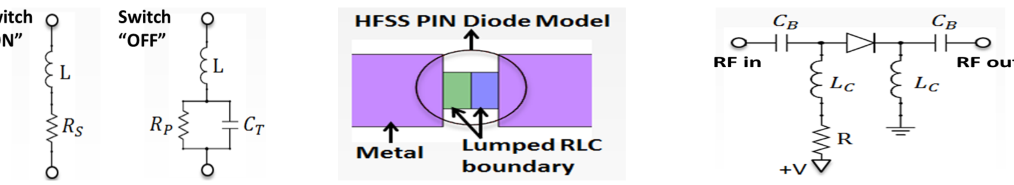
Typically when frequency reconfigurable antennas are designed, the main focus is on changing the input impedance, which determines the overall matching response [2]. For an antenna to be capable of covering the most applications (frequency bands), contiguous matching bands (modes) and a comprehensive wideband mode (covering all of the narrower matching bands) are desired, and some such designs are now presented. In [3] PIN diodes are located in a microstrip feed line, which is electromagnetically coupled to a slot antenna, to vary the feed line length which varies the operating frequency. Two contiguous wideband modes 64% and 55% are achieved, but this design lacks the comprehensive wideband mode and the radiating slot is too large for an array element (1.1λ). In [4] a planar monopole antenna (PMA) is combined with a reconfigurable coplanar waveguide (CPW) filter, and varactor diodes are used to reconfigure the filter. Five contiguous narrowband modes with 39% total reconfigurable bandwidth are achieved in addition to a wideband mode with 58% bandwidth, but the width of the PMA with biasing lines (1.1λ) makes it unsuitable for an array element.

Few frequency reconfigurable antenna designs focus on designing an array element, and these designs do not have the desired wide matching bandwidths. In [5] an reconfigurable phased array antenna element is created by using MEMS switches to connect/disconnect a capacitive strip located at the edge of a patch antenna, thus changing the resonant frequency. The design has 2 contiguous narrowband modes with 5.2% total reconfigurable bandwidth. In [6] MEMS capacitors are used to alter the length of a perturbing slot in a triangular patch phased array antenna element (0.3λ edge length) which changes the resonant frequency. A frequency reconfigurable bandwidth of 20% is achieved with 5 contiguous narrowband modes.

The goals of the design in this paper are to create a compact frequency reconfigurable antenna that can be used as an array element ($< 0.6\lambda$ at highest frequency of operation), improve upon the possible total reconfigurable bandwidth for a reconfigurable array element (> 20%), and have a comprehensive wideband mode option. The spirograph planar monopole antenna (SPMA) was originally presented in [7] and was used as the radiating element in a 1x4 beam scanning array in [8]. A frequency reconfigurable SPMA design is presented in this paper. This design has 3 wideband modes which provide contiguous coverage over 104% bandwidth, including a comprehensive wideband mode which provides 96% bandwidth. A brief introduction to using RF PIN diodes in antenna design is presented in Section 2. Section 3 describes the antenna geometry, and simulation results are presented in Section 4.

2. Using RF PIN Diodes as Switches in Antenna Design

RF PIN diodes can be used as “switches” to aid in the design of frequency reconfigurable antennas. At RF frequencies the PIN diode behaves as a variable resistor, but with slightly more complicated circuit models for the ON/OFF states [9], as shown in Fig. 1a. Both the ON and OFF states have a package inductance L. The equivalent circuit for the ON state (forward biased) has a low resistance R_s which contributes to the insertion loss. The equivalent circuit for the OFF state (zero or reverse biased) has the parallel combination of the parallel reverse bias resistance R_P and the total capacitance C_T, which contributes to the isolation. The OFF state resistance is determined by $R_P = V_R/I_R$, where I_R is the reverse leakage current when a test voltage of V_R is applied. All of the values necessary to form the circuit models are given in a standard PIN diode data sheet. The PIN diode is modeled in HFSS using 2 series lumped RLC boundary conditions, as shown in Fig. 1b. The first one is L and the second one is either the R_S for the ON state or the parallel combination of R_P and C_T for the OFF state. An example of how to use the RF PIN diode as a series switch is shown in Fig. 1c. A resistor R is used to achieve the desired ON state current. To keep the RF signal out of the DC bias lines, RF choke inductors L_C are used. To keep the DC out of the RF portion of the circuit, DC blocking capacitors C_B are used.



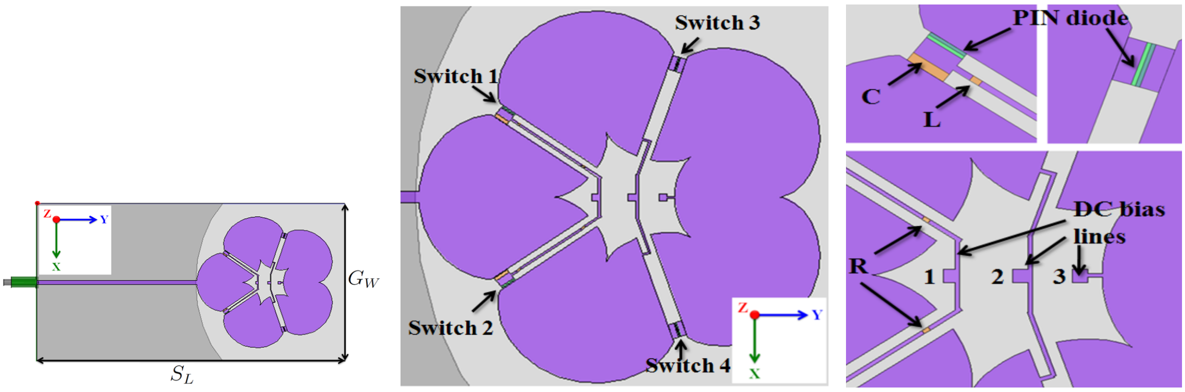
(a) (b) (c)

Figure 1: RF PIN diode: (a) Equivalent circuit model; (b) HFSS model; (c) Used to create series switch.

3. Antenna Geometry

The 5-pointed SPMA of [7] was scaled to operate in the 1-3 GHz frequency range, and modified to be frequency reconfigurable (see Fig. 2). The 50 Ω microstrip feed line (with end-launch SMA connector) and radiating element are on the top layer of 0.508 mm thick Rogers RT/Duroid 5880 ($\epsilon_r = 2.2$, $\tan\delta = 0.0009$) substrate, and the ground plane is on the bottom. The maximum diameter of the SPMA element is 51.8 mm (0.54λ at 3.1 GHz), the average ring thickness is 13.3 mm, $G_W = 62.5$ mm and $S_L = 11.5$ cm. The ground plane length varies from 59.3 - 69.3 mm. The SPMA is segmented by slicing a 1.85 mm gap (to fit two 0402 package size components) at the angles of: 36°, 108°, 252°, and 324°. For the switch 1 and 2 gaps, a DC blocking capacitor is in series with a PIN diode. The switch 3 and 4 gaps contain only a PIN diode each. Bias lines 1 and 3 are for positive voltage, and each contains an 0402 size resistor close to the beginning of the bias line (near the center of the SPMA). Bias line 2 is for ground. Bias line 1 has a RF choke inductor close to the PIN diode. The PIN diodes are located at the outer edge of the SPMA since the current is most concentrated along these edges.

There are three possible configurations. Case 1 is when all PIN diodes are OFF (all bias lines connected to ground), so only the first segment of the SPMA is connected to the feed line. Case 2 is when only switch 1 and 2 are ON (bias line 1 connected to positive voltage, bias lines 2 and 3 grounded), so three segments of the SPMA are connected to the feed line. Case 3 is when all PIN diodes are ON (bias lines 1 and 3 connected to positive voltage, bias line 2 grounded), so all segments of the SPMA are connected to the feed line. The PIN diodes modeled are Skyworks SMP1340. The HFSS model values for the ON state are: L = 0.45 nH and R = 1.2 Ω, and the model values for the OFF state are: L = 0.45 nH, R = 5 MΩ, and C = 0.14 pF. The RF choke inductors are 2.2 nH, the DC blocking capacitors are 15 pF, and the bias line current regulating resistors are 47 Ω (assuming a bias voltage of +1.5 V).

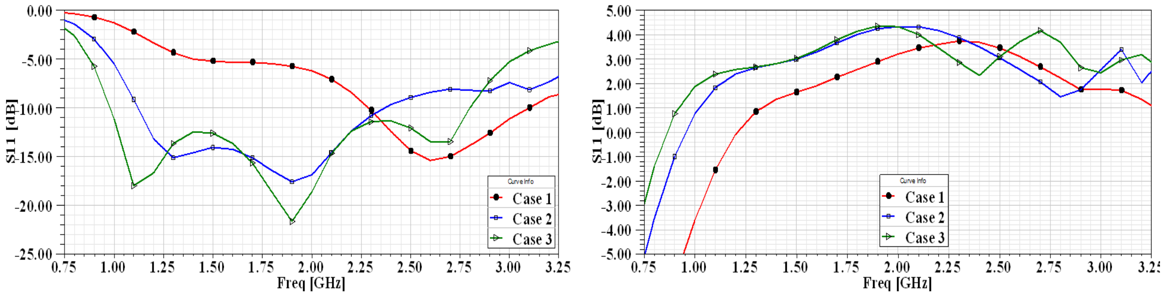


(a) (b) (c)

Figure 2: HFSS model of frequency reconfigurable SPMA: (a) Top view; (b) Zoomed-in top view; (c) Close-up of bias circuitry.

4. Simulated Antenna Performance

The simulated performance of the frequency reconfigurable SPMA is now presented. The width of the ground plane G_W was varied from 52 mm to 67.65 mm to optimize the design (not shown for the sake of brevity). The best case to achieve optimum impedance matching for each case simultaneously was G_W = 62.5 mm. The $S_{11} \leqq$ -10 dB impedance matching (shown in Fig. 3a) is as follows: case 1, 2.29 - 3.10 GHz (30.1%); case 2, 1.12 - 2.37 GHz (71.6%); and case 3, 0.98 - 2.8 GHz (96.5%). The total reconfigurable bandwidth is 0.98 - 3.10 GHz (103.9%). The peak realized gain for case 1, 2, and 3 is shown in Fig. 3b. Among the 3 cases, the peak realized gain varies from 1.7 - 3.7 dBi. The 3-D realized gain radiation patterns for one frequency from each case are shown in Fig. 4. The maximum cross-polarization (not shown) for case 1, 2, and 3 is -9.1, -14.8, and -11 dBi, respectively. This antenna has an omnidirectional pattern with relatively low cross-polarization (lower than the co-polarization).



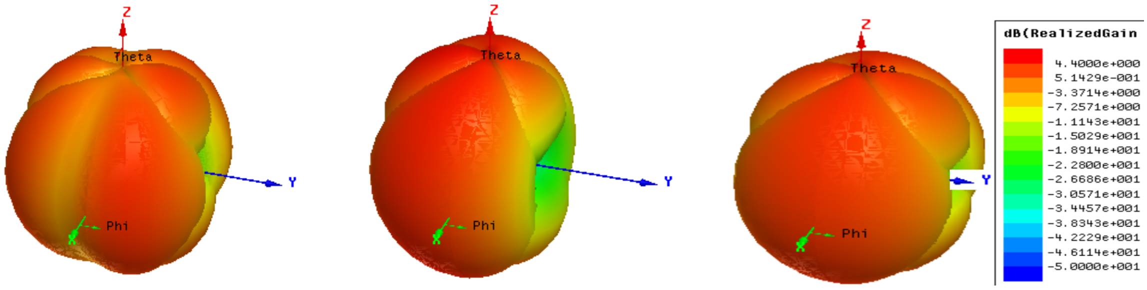
(a) (b)

Figure 3: Performance of case 1, 2, and 3: (a) S_{11}; (b) Peak realized gain.

Finally, the current distribution for each case is examined. The magnitude of the surface current distribution for one frequency from each case is shown in Fig. 5. For case 1, although only the first segment is connected to the feed line some current is still electromagnetically coupled to the other segments. For case 2, the current plot indicate switch 1 and 2 are ON. For case 3, the current plot indicates all switches are ON.

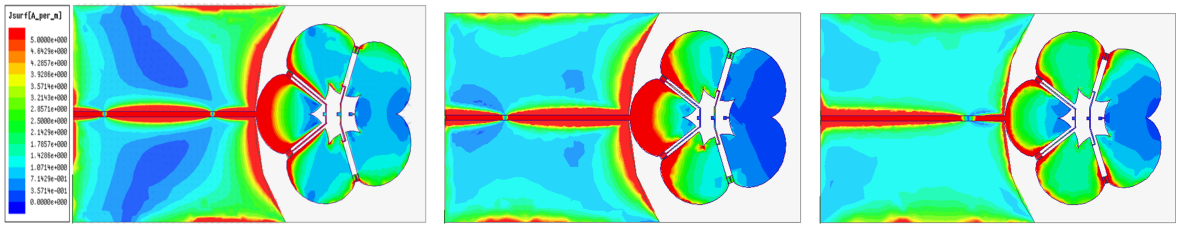
5. Conclusions

A frequency reconfigurable SPMA was presented. The radiating element is compact (0.53λ at 3.1 GHz) such that it can be used as an array element. It has 3 modes: case 1, 2.29 - 3.10 GHz (30.1%); case 2, 1.12 - 2.37 GHz (71.6%); and case 3, 0.98 - 2.8 GHz (96.5%). Case 1 and 2 provide contiguous coverage, and case 3 covers almost the entire range of case 1 and 2. Thus this antenna provides continuous coverage for 0.98 - 3.10 GHz (104% impedance bandwidth). The gain for all cases ranges from about



(a) (b) (c)

Figure 4: 3-D realized gain radiation pattern for: (a) Case 1 at 3.1 GHz; (b) Case 2 at 1.7 GHz; (c) Case 3 at 1 GHz.



(a) (b) (c)

Figure 5: Surface current distribution for: (a) Case 1 at 3.1 GHz; (b) Case 2 at 1.7 GHz; (c) Case 3 at 1 GHz.

1.7 - 3.7 dBi, the cross polarization is relatively low, and the patterns are omnidirectional.

Acknowledgments

This work was partially supported by National Science Foundation CAREER grant ECCS-0845822.

References

[1] J. L. Volakis, *Antenna Engineering Handbook*, McGraw-Hill, New York, NY, 4th ed., 2007.

[2] J. T. Bernhard, *Reconfigurable Antennas*, Morgan & Claypool, 2007.

[3] M. Davidovic *et al.*, "Reconfigurable UWB antenna operating in two different sub-bands," Antennas Propag., Proc. European Conf., pp. 1-5, 2010.

[4] A. Tariq and H. Ghafouri-Shiraz, "Frequency-reconfigurable monopole antennas," IEEE Trans. Antennas Propag., vol. 60, no. 1, pp. 44-50, 2012.

[5] R. Simons *et al.*, "Reconfigurable array antenna using microelectromechanical systems (MEMS) actuators", IEEE Antennas Propag. Soc. Int. Symp., vol. 3, pp. 674-677, 2001.

[6] L. Feldner *et al.*, "RF mems reconfigurable triangular patch antenna," IEEE Antennas Propag. Soc. Int. Symp., vol. 2A, pp. 388-391, 2005.

[7] J. T. Rayno and S. K. Sharma, "Compact spirograph planar monopole antenna (SPMA) covering C-/X-band with invariant radiation pattern characteristics," IEEE Trans. Antennas Propag., Submitted.

[8] J. T. Rayno and S. K. Sharma, "Beam steering performance of a C- and X-band compact spirograph PMA (SPMA) array", IEEE Antennas Propag. Soc. Int. Symp., 2012.

[9] Skyworks, *Application Note: Design with PIN Diodes*, April 2009.