5.8 GHz Retrodirective Array Phase Modulator

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Abstract- A Retrodirective Array Phase Modulator (RAPM) has been design for the unlicensed ISM band. Communication is implemented using Quadrature Phase Shift Keying (QPSK) through modulated backscatter. A Van Atta Array was created using Single Pole Four Throw (SP4T) switches and controlled by a low power microcontroller. This paper describes the design process and discusses the results.

I. Introduction

RF energy harvesting has become a popular research topic due to the need to operate electronics in remote, inaccessible locations. For instance, a sensor attached to an RF energy harvesting system may be embedded in the structure of a building and report data on the integrity of the structure when it is hit with RF energy.

RAPM is an attractive way to implement ultra low power communication. In a RAPM, QPSK states are created by a Van Atta Array. A Van Atta Array is essentially a corner reflector that reflects incoming waves back towards the source with a shifted phase. The Van Atta Array does not require active beam steering so additional components that consume power such as phase shifters and local oscillators are not needed [1]. By having transmission lines of different lengths, four different phase shift states are created.

The incoming RF energy can be directed through any of the four lines using low loss Skyworks SKY12233 SP4T switches. These state of the art switches have an insertion loss of only 2dB at 4-6 GHz. The switches are controlled by a TI MSP4302013 low power microcontroller as shown in Figure 1. This microcontroller requires only 220μA in active mode. By keeping power consumption low this system becomes a candidate to run off of harvested RF energy.

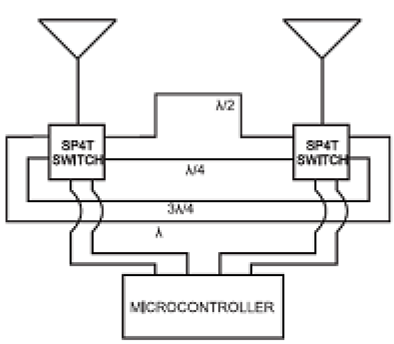

Fig. 1. Retrodirective array phase modulator schematic [1].

II. Design

The design of the RAPM board required transmission line design, microcontroller implementation, and PCB development using software new to the designers.

A. Transmission Line Design

In order to transmit QPSK signals via RAPM, transmission lines must be designed to shift the phase by 90°, 180°, 270°, and 360° (0°) at 5.8 GHz. The designers chose to implement microstrip lines instead of coplanar waveguides because coplanar waveguides, particularly those surrounded by thin ground traces and vias, are difficult to model in ADS. Even though microstrip traces are wider than coplanar waveguides for a fixed Z_o, the authors believed the lines could be modeled more accurately as microstrips.

Parameter	Value
H (Substrate Thickness)	31 mil
ε_r (Relative Permittivity)	4.8
μ_r (Relative Permeability)	1
Cond (Conductivity)	$6x\ 10^7$ S (Cu)
T (Trace Thickness)	35um (1 oz Cu)

Table 1. Substrate Parameters

The FR-4 substrate parameters chosen to model the microstrip lines are shown in Table 1. All lines were modeled using ADS microstrip components, such as microstrip lines and microstrip corners. The lines were designed for a characteristic impedance of 50 Ω, which corresponds to a microstrip width of roughly 56 mils according to LineCalc. The length of each line segment was adjusted using the ADS tuning feature. In order to minimize crosstalk, the parallel segments of each line were placed as far apart as possible. All lines were designed and arranged to fit with the provided switches. Since the pins of the switches are 10 mils wide, the microstrip lines were tapered down to contact these pins. The lines were tapered over a short distance, so the tapers were not included in the simulations. The lines connecting each switch to an antenna were each designed to have a phase shift of 0° so only the RAPM lines would shift the signal phase. To connect the RF lines to the switches, 45° angled microstrips were used. The designers could find no 45° angle microstrip components in ADS so a 45° circular bend was used to model the angle.

The complete ADS simulation schematic can be seen in the Appendix.

+90 deg line

db(S(5,5)[8])	db(S(6,5)[8])	phase(S(6,5)[8])
-19.354	-0.677	90.650

180 deg line

db(S(3,3)[8])	db(S(4,3)[8])	phase(S(4,3)[8])
-18.745	-0.445	-179.923

-90 deg line

db(S(1,1)[8])	db(S(2,1)[8])	phase(S(2,1)[8])
-36.242	-0.234	-90.086

0 deg line

db(S(7,7)[8])	db(S(8,7)[8])	phase(S(8,7)[8])
-11.517	-2.106	10.522

Antenna line

db(S(9,9)[8])	db(S(10,9)[8])	phase(S(10,9)[8])
-40.134	-0.935	1.619

Fig. 2. Simulated microstrip results.

Simulated results at 5.8 GHz for each line are shown in Figure 2. The simulated phase shifts closely match the desired results. The insertion loss of each line except for the 0° line is below 1 dB, and the return loss for each line is greater than 11.5 dB. The 0° line is the lossiest, which is to be expected because it is the longest line. The phase of this line could not be reduced to 0° because of physical constraints.

B. Microcontroller Implementation

The microcontroller was setup to use a 4-wire JTAG interface using the TDI, VPP, TMS, and TCK signals. The microcontroller was required to output a random QPSK signal. A simple program was written for an algorithm that would output four square waves at the same frequency determining the position of the SP4T switches. One square wave would be asserted high to turn that connection "on" while the other three were turned "off." This algorithm would run continuously to shift between QPSK states and ideally produce the IQ diagram seen in Figure 3.

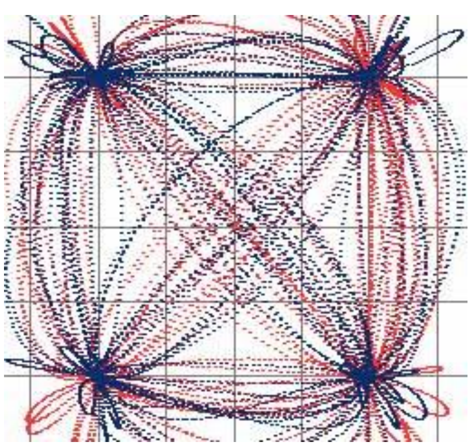

Fig. 3. Ideal QPSK IQ diagram.

C. PCB Development

The board design was completed using CadSoft Eagle. Microcontroller pins were made available through 7 pin connectors. This allowed for easy access for JTAG programming and flexibility in design. The design allowed for the microcontroller to be powered by a Lithium Ion battery or an external power supply. A test trace for the +90° line was also laid out. The board was milled on 31 mil FR4 with 1 oz copper traces. The schematic of the PCB can be seen in the Appendix.

III. Development

All PCBs were fabricated using Georgia Institute of Technology fabrication equipment. This allowed for quick board development, but was limited in precision.

The size of the SKY13322 switches made it difficult to fabricate functional boards. The SKY13322 pins are less than 10 mils apart. Even with advanced milling equipment, several iterations were required to accurately fabricate the board. When populating the board, it was discovered that the SP4T switches also required a ground connection on the underside of the chip. This packaging detail was not accounted for in the original design. Unfortunately, the board layout contained traces which ran under the SP4T switches that would short to ground. To work around this problem, attempts were made to remove the pin on the underside of the chip, but it was embedded too far into the package. There was also a possibility that an insulating material could be inserted between the traces and the chip, but these materials were either too thick or too dry to be used. The design flaw of having traces run under the SP4T switches prevented the RAPM board from working.

It was impossible to make slight modifications to redesign the board. This design implemented microstrip lines for better model accuracy. Due to the size of the SP4T switch and the microstrip lines, the only way to route the digital inputs to the SP4T switches was to go under the chip. Since the digital inputs must run outside the chip due to the backside ground pin, there is not enough space to use microstrip lines. Smaller coplanar waveguide lines must be used. Thus, redesigning the board would have required a complete redesign of the transmission lines. Due to time constraints this could not be completed. The populated board without switches is shown in Figure 4.

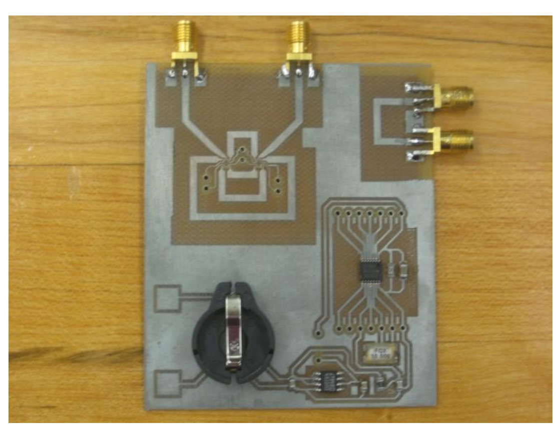

Fig. 4. Populated RAPM board.

Additional difficulties occurred in attempting to program the microcontroller. JTAG programming can use either a 2-wire or a 4-wire interface. This design was made with a 4-wire interface. Unfortunately, designs with the 2-wire interface seemed to be more successful. Programming using the 4-wire interface, resulted in a "The device is not found" error message. Attempts to modify the board to change it to a

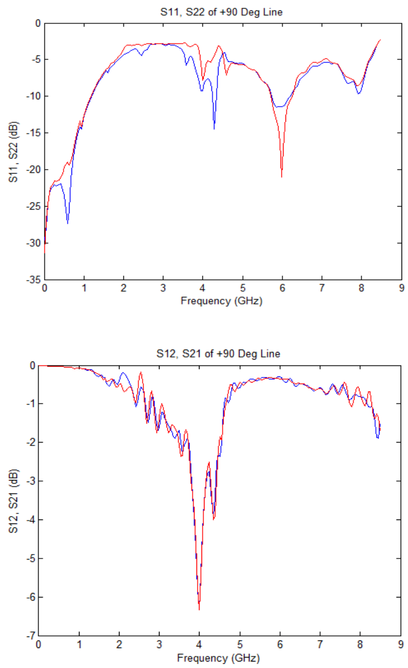

Fig. 5. Measured s-parameters of +90° line.

2-wire interface were made, but the board was not designed for this purpose. This particular error may have also arisen if the computers used were not compatible with the hardware or if there was a problem with the chip. This problem prevented any test of whether the microcontroller functioned properly.

IV. Results

Although the switches were impossible to attach correctly, the +90° line test structure could still be tested. The other lines could not be laid out as test structures due to their bends and their length. The +90° line including tapers was connected directly to two SMA adapters to measure the S-parameters. The measured S-parameters are in Figure 5, and the measured phase shift is in Figure 6. The return loss is around 10 dB, the insertion loss is around 0.3 dB, and the phase shift is around -65° at 5.8 GHz. The return loss peaks near 6 GHz and the insertion loss is very low at this frequency, so the line appears to have the correct Z_0 at the design frequency. The dielectric constant was varied in simulation from 3.8-5.8 to account for the unpredictable dielectric constant of FR-4, but the phase does not deviate nearly as drastically from the simulated phase as the measured phase does.

The difference between the measured and simulated values is probably due to the solder joints and connections to SMA connectors. These are not modeled in the simulations, and these connections are long enough to alter the phase characteristics of the line. EM simulating the microstrip lines would also help to improve the designed lines. The authors were severely constrained by time limitations, so they did not have time to perform these simulations. Microstrip lines in future iterations of this project could be improved by fabricating and measuring test structures before attempting to implement the lines in a RAPM. This way the actual dielectric constant and optimal lengths could be obtained

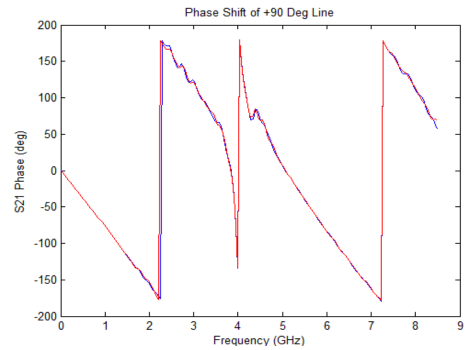

Fig. 6. Measured phase shift of +90° line.

experimentally. Placing test structures for de-embedding the solder joints and SMA connectors from the measured s-parameters could prove useful as well.

V. Conclusion

The concept of low power communication using a RAPM system holds great promise. However to achieve a reliable product, the PCB board must be professionally fabricated out of house. Due to the size of the low loss switches, microstrips cannot be used. Coplanar waveguide RF traces are required to make room for digital inputs. The bill of materials in Table 2 shows the total system cost is just over $20. The low cost would make the system very attractive for RFID and remote sensing applications.

References

[1] G. A. Koo, Y. A. Lu, and G. D. Durgin. "Retrodirective Array Phase Modulation for Ultra Low-Power Communications," *IEEE Antennas Wireless Propag. Lett.* 2010.

[2] K. Chang, I. Bahl, and V. Nair, "Transmission Lines and Impedance Matching Techniques, " in *RF and Microwave Circuit and Component Design for Wireless Systems* . New York: Wiley, 2002, pp. 105–169.

Item	Part	cost	qty	Item cost
1	bat holder	$1.13	1	$1.13
2	crystal resonator	$1.61	1	$1.61
3	SP4T GaAs	$1.12	2	$2.24
4	3v Reg	$3.00	1	$3.00
5	low power uC	$1.80	1	$1.80
6	SMA Conn	$5.10	2	$10.20
7	47.5k	$0.05	1	$0.05
8	2.2nF	$0.03	1	$0.03
9	820nF	$0.16	2	$0.32
10	100pF	$0.02	1	$0.02
11	10uF	$0.09	1	$0.09
			Total:	$20.49

Table 2. RAPM board bill of materials.

Appendix

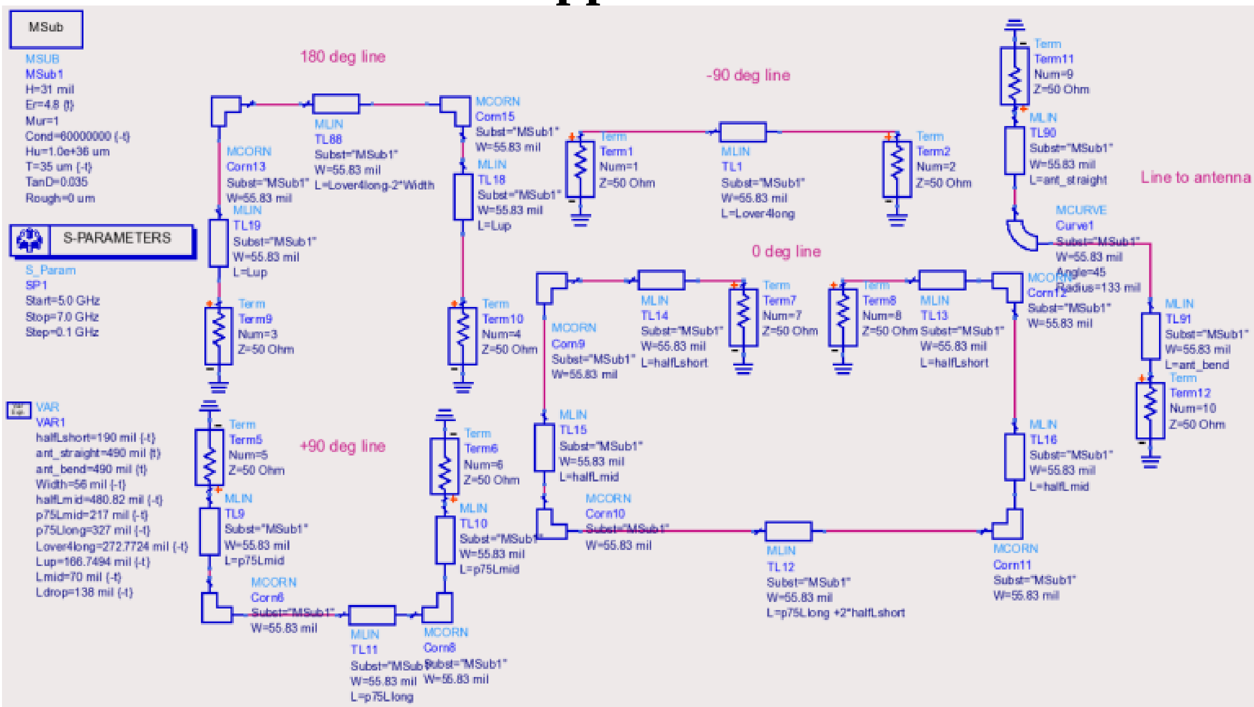

Fig. A.1. ADS simulation schematic for microstrip lines

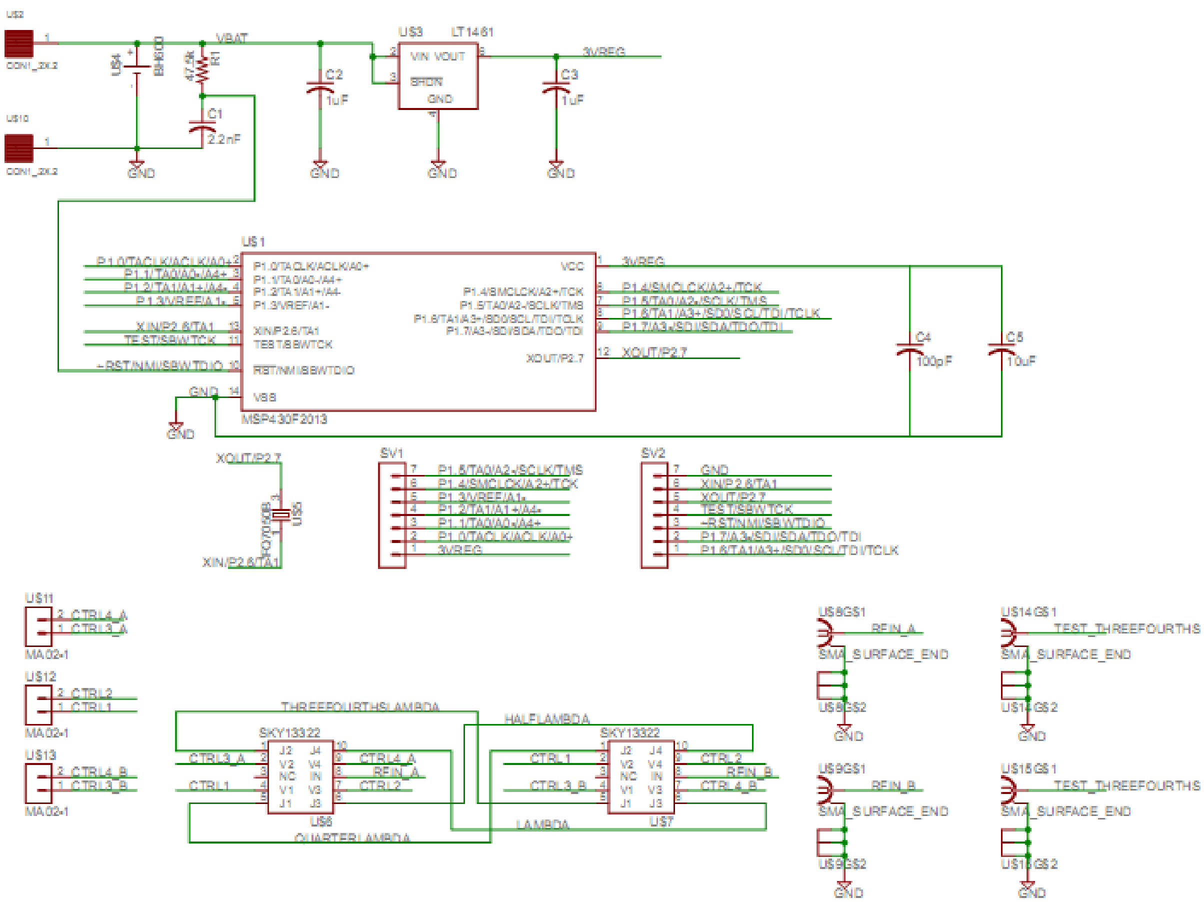

Figure A.2. RAPM PCB schematic