Designing Loop Antennas for the rfPIC12F675

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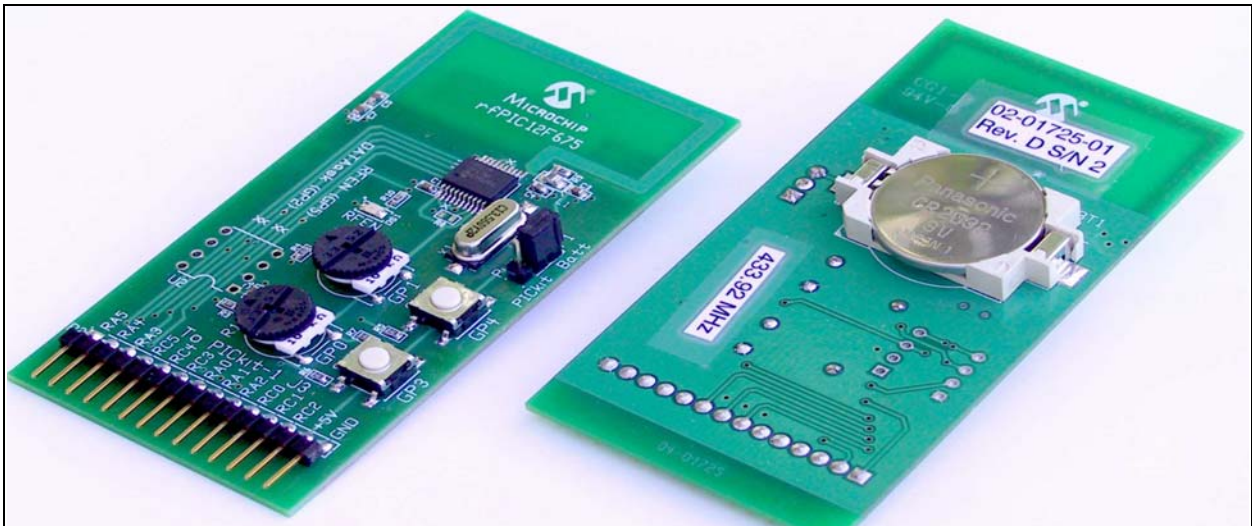
1.0 INTRODUCTION

This application note describes the design of a single-ended loop antenna for rfPIC12F675 transmitters. The PCB design will cover all 3 frequency bands from 290 MHz through 930 MHz with a few component value changes.

The previous Microchip RF transmitters had balanced outputs which required twice as many components to bias the power amplifier and match impedance. The rfPIC12F675 uses fewer components, delivers almost 10 dB more output power to the antenna, and increases the maximum frequency to 930 MHz.

This application note also documents the tuning and testing of the antenna design to avoid a manufacturing step for tuning. A picture of the finished board is shown in Figure 1. For more details on RF regulatory limits and compliance testing see Application Note AN242, "*Designing an FCC Approved ASK rfPIC Transmitter.*"

FIGURE 1: SINGLE-ENDED SMALL LOOP ANTENNA BOARD FOR THE rfPIC12F675



A. Top View B. Bottom View

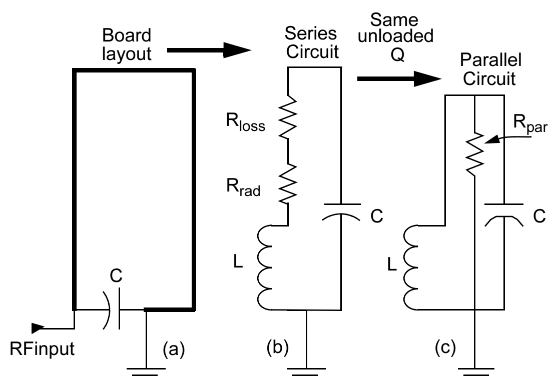
2.0 TAPPED CAPACITOR DESCRIPTION

The small magnetic loop antenna is one of the most popular antenna designs for handheld applications and for applications where more efficient antennas would be too large. The small magnetic loop antenna is a simple loop of wire or PCB trace that is tuned to resonate at a desired frequency. The challenge is matching its impedance to the transmitter output for maximum power transfer and harmonic filtering. Complexity is increased when all component tolerances are taken into account to avoid a manufacturing step for tuning.

The two most common topologies for matching the antenna impedances are tapped capacitor and tapped inductor, or transformer designs. This explanation uses the tapped capacitor topology to match the antenna impedance, as shown in Figure 2. Tapped inductor design for balanced outputs is documented in Application Note AN831, "*Matching Small Loop Antennas to rfPIC™ Devices*."

Small loop antennas have an inherently high Q that must be reduced to simplify manufacturing. With the Q under 20, standard tolerance parts can be used while still eliminating the tuning step from manufacturing. The Q is reduced by putting a resistor in parallel with the antenna.

FIGURE 2: LOOP ANTENNA ANALYSIS



a) Loop antenna physical implementation
b) The standard loop antenna model
c) Transformed resistances into parallel

The radiation resistance of an electrically small loop (perimeter < 0.3λ), is given[5] as:

$$R_{rad} = 320\pi^4 \left(\frac{A^2}{\lambda^4}\right)$$

A = loop area inside center of trace width (m^2)
λ = speed of light/frequency = wavelength (m)

Assuming the PCB antenna trace width is much greater than its thickness, and its thickness is much greater than skin depth, the trace resistance is given by:

$$R_{loss} = \frac{l\sqrt{\frac{\pi f \mu_0}{\sigma}}}{2w}$$

l = total perimeter of center of antenna trace (m)
w = width of the trace (m)
σ = conductivity, copper = 5.8E7 S/m
μ_0 = permeability of air = 1.256E-6 H/m

The total series resistance is the sum of the radiation resistance, trace loss, and ESR of the capacitors:

$$R_s = R_{rad} + R_{loss} + R_{esr}$$

The radiation efficiency of the loop is commonly given as:

$$\eta_r = \frac{R_{rad}}{R_s}$$

Increasing R_{rad} or reducing R_{loss} or R_{esr} will improve the loop efficiency and transfer more of the output power to your receiver. A ceramic C0G capacitor's ESR is typically 0.2 to 0.6 Ω at UHF frequencies; variable capacitors and ceramic X7R capacitors values are usually higher.

The inductance of the loop must be found to select a capacitor value for resonance. An equation[6] to estimate the inductance of this loop with about 95% accuracy is:

$$L = \frac{\mu}{2\pi} l \ln\left(\frac{8A}{lw}\right)$$

The equation to find the capacitor value is:

$$C = \frac{1}{4\pi^2 f^2 L}$$

To find the impedance of this antenna, the series resistance must be converted to parallel resistance. First we calculate the unloaded Q from the series losses:

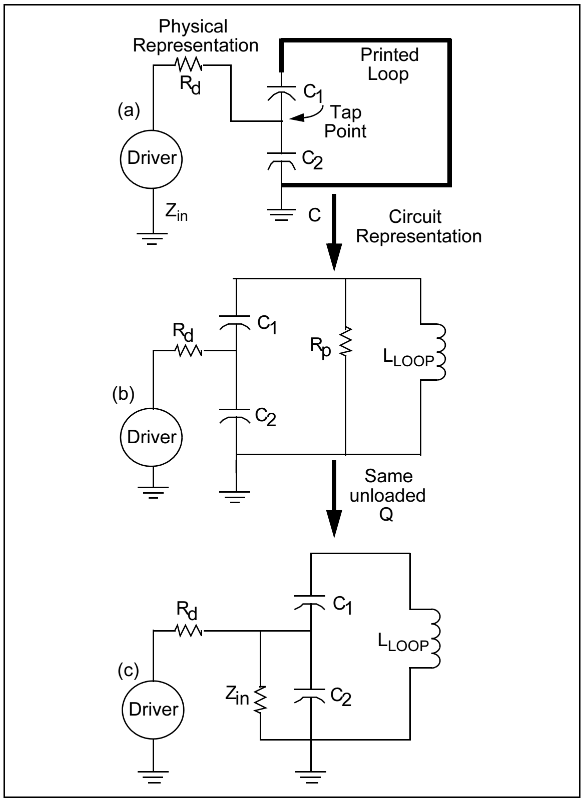
$$Q_s = \frac{2\pi f L}{R_s}$$

For high values of Q, the equivalent parallel L and C are about equal to the series values. The parallel resistance is found with this equation:

$$R_p = R_s (Q_s^{\,2} + 1)$$

At resonance, the L and C in Figure 2(c) cancel, leaving the parallel resistance as the antenna impedance. This value is many times larger than the output impedance of the transmitter. Instead of connecting to the node between the L and C, we can tap into the inductor, or in this case, the capacitor. This reduces the impedance by the ratio of the tap point to make a better match with the transmitter. This tapped capacitor circuit is shown in Figure 3.

FIGURE 3: IMPEDANCE MATCHING



With driver impedance equal to the antenna input impedance, the maximum power will be transferred to the antenna.

Note:	Loading the antenna will reduce the loaded Q to half the unloaded Q at resonance.

Solving the circuit at resonance for antenna impedance Z_{in} results in:

$$Z_{in} = \left(\frac{C_1}{C_1 + C_2}\right)^2 R_P$$

Algebraically manipulating this equation with the previous equations results in these solutions for C_1 and C_2:

$$C_1 = \frac{1}{4\pi^2 f^2 L - 2\pi f \sqrt{Z_{in} R_s}}$$

$$C_2 = \frac{1}{2\pi f \sqrt{Z_{in} R_s}}$$

The last term in the numerator for C_1 is the inverse of C_2, so the equation is rewritten as:

$$C_1 = \frac{1}{4\pi^2 f^2 L - \frac{1}{C_2}}$$

Typically C_2 will be much larger than C_1. In this case, C_1 tunes the resonant frequency while C_2 independently tunes the antenna impedance. This makes tweaking the final design much easier. For example, the antenna impedance could be decreased on a tuned board by only increasing C_2, without a compensating decrease in C_1 while maintaining near optimal tuning.

3.0 DESIGNING THE CIRCUIT BOARD

This design will be done at 433.92 MHz since this frequency is one of the most common worldwide for unlicensed remote control applications. The example circuit only does ASK modulation, but the antenna design would be the same if FSK modulation were required. The other fixed design parameter is the transmitter output impedance. For the rfPIC12F675K/675F transmitters use 300 Ω and for the rfPIC12F675H transmitter use 250 Ω.

The loop size and trace width will be determined as the circuit board is planned. Keep the antenna trace about 2 mm thick and the area as large as possible. These equations will still work if the loop is not rectangular, but the area and perimeter must be calculated differently. These equations will not be accurate if components or traces are in the middle of the loop or very close to the loop. Using the ground plane as one side of the loop makes the loop effectively larger while lowering resistive losses.

On this example board, shown in Figure 4, the capacitor designators change from Figure 3. Capacitors C5 and C6 in series make up the theoretical C_1, and C4 replaces C_2. Two capacitors were used to make C_1 more selectable. The series capacitors behave like parallel resistors, permitting many combinations of values between standard capacitor values. This is important to finely tune your board to the exact resonant frequency. A less flexible alternative would be to build several boards and vary the antenna length on each one until it was optimized for a standard-value capacitor.

The obvious disadvantage of series capacitors is that their ESR values sum up to reduce efficiency. In the next section, you will see that no extra power is lost since the antenna Q must be reduced for tuneless manufacturing.

When laying out your board, be sure to place pads for C_1 and C_2 that can accommodate trimmer capacitors. On this board, a larger trimmer capacitor fits nicely instead of the two 0603 parts, C5 and C6. Since there was not enough room for a trimmer capacitor at C4, a short jumper wire from the capacitor to ground had to suffice during tuning.

On the example layout, there is also an 8-pin DIP socket in parallel with the microcontroller for in-circuit programming and firmware development, as described in the rfPIC12F675 data sheet. Since the microprocessor core is the same as for a rfPIC12F675, the tools for that processor will work on this board and your software will perform identically. On this board, you can either lift the processor pins as shown in the rfPIC12F675 data sheet, or cut the traces marked with an silk screen X to do software emulation from the DIP socket.

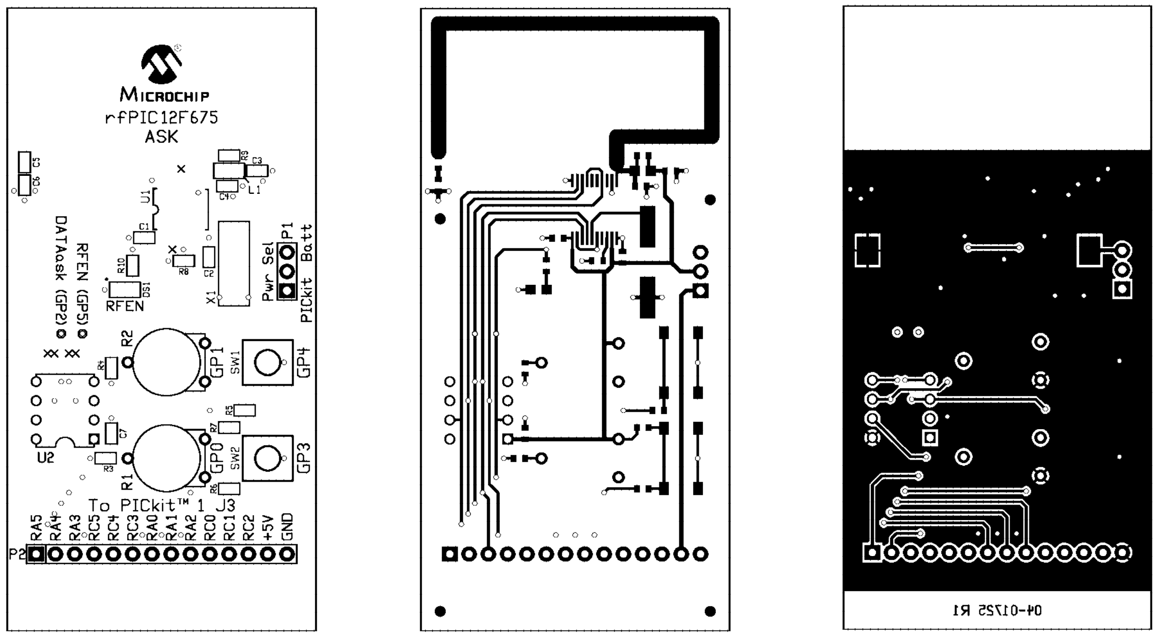
This board also has a 14-pin header compatible with the PICkit™ 1 Flash Starter Kit header J3. This makes firmware development and in-circuit programming simple and low cost. The power supply jumper P1 must be set to use external PICkit™ power for programming or battery power for stand-alone operation.

With the board layout complete, the antenna can be measured to calculate the capacitor values. In this example (Figure 4), the loop height is approximately 0.016m and its width is 0.035m. The trace width is 0.002m. The sum of three capacitor ESR values is about 1.7 Ω. Plugging these numbers into the equations from the previous section results in:

- R_{rad} = 0.0573 Ω
- R_{loss} = 0.289 Ω
- Efficiency = 2.8%
- L = 68.3 nH
- C_1 = 2.27 pF
- C_2 = 14.8 pF

Experimental evidence has found these capacitor values to be approximately 15% high. This is very good considering the inductance and loop resistance equations are approximations, the circuit board has irregularities, and actual components used are only ±5% accurate. C_1 gets even closer to the actual value when approximately 1 nH series inductance is added for each of the capacitors to the loop inductance formula. The actual capacitor values and part numbers are shown in the Bill of Materials (BOM), Figure 6.

FIGURE 4: BOARD LAYOUT LAYERS



A) Silk Screen B) Top C) Bottom

FIGURE 5: TRANSMITTER SCHEMATIC

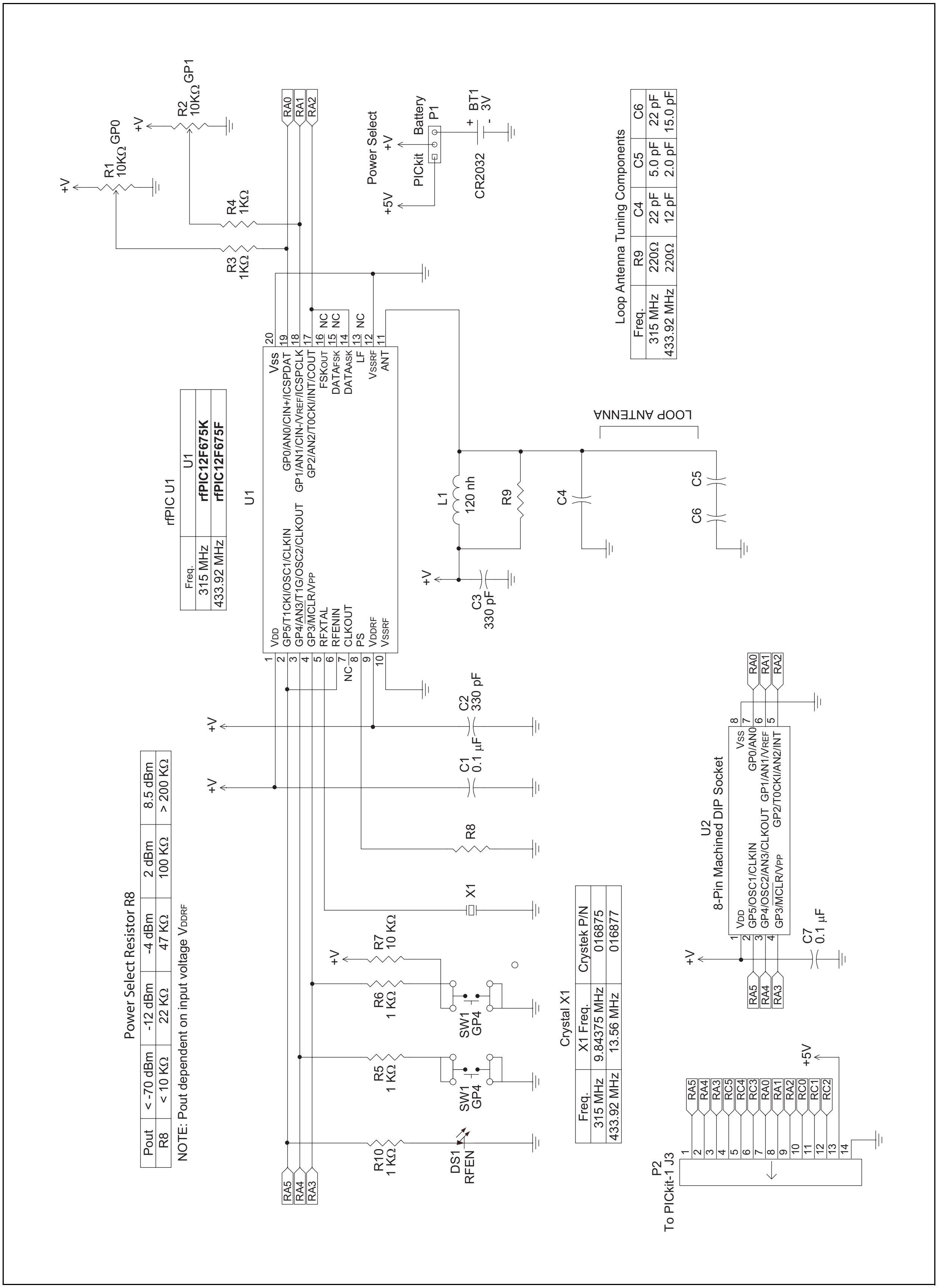


FIGURE 6: BILL OF MATERIALS

Quantity	Designator	Value	Description	Order Form	Part Number
1	C4	12 pF, NP0, 0603	Capacitor, Ceramic Chip	Digi-Key	PCC120ACVTR-ND
1	C5	2.0 pF, NP0, 0603	Capacitor, Ceramic Chip	Digi-Key	PCC020CVTR-ND
1	C6	15 pF, NP0, 0604	Capacitor, Ceramic Chip	Digi-Key	PCC150ACVTR-ND
2	C2, C3	330 pF, X7R, 0603	Capacitor, Ceramic Chip	Digi-Key	PCC331ACVTR-ND
2	C1, C7	0.1 μF, X7R, 0603	Capacitor, Ceramic Chip	Digi-Key	PCC1762TR-ND
1	R8	Not populated			
2	R9	220 Ohm, 0603	Resistor, Chip, Thick Film	Digi-Key	P220GTR-ND
4	R3, R4, R5, R6, R10	1K ohm, 0603	Resistor, Chip, Thick Film	Digi-Key	P1.0KGTR-ND
1	R7	10K ohm, 0603	Resistor, Chip, Thick Film	Digi-Key	P10KGTR-ND
1	R1	220K ohm, 0603	Resistor, Chip, Thick Film	Digi-Key	P220KGTR-ND
2	R1, R2	10K ohm	Potentiometer	Digi-Key	3325E-103-ND
1	DS1	SMT LED 0805	Red	Digi-Key	67-1552-1-ND
1	L1	120 nH, 0805	Inductor, Chip	Digi-Key	TKS2387CT-ND
1	P1	3-pin header	Single row, 0.025” square, .1” spacing	Digi-Key	S1012-03-ND
1	P2	14-pin Right Angle Header	Single row, 0.025” square, right angle post	Digi-Key	A26510-ND
1		2-pin shunt		Digi-Key	S9000-ND
1	BT1	KS1060	Coin Cell Battery Holder	Digi-Key	1060KTR-ND
1	Battery	CR2032	Lithium Cell Battery	Digi-Key	P189-ND
2	SW1, SW2	SPST momentary	Pushbutton switch	Digi-Key	SW415-ND
1	X1	13.56 MHz	Crystal, HC-49/S	Crystek	016877
1	U1	rfPIC12F675F	Transmitter + PICmicro	Microchip	rfPIC12F675K
1	U2		8-pin machined socket	Digi-Key	ED3108-ND

4.0 RF TESTING AND TUNING

If you made absolutely no changes to the RF transmitter circuitry, components, or the loop antenna area then you may skip ahead to the manufacturing section.

If you changed the transmitter frequency by changing the crystal, be sure that you are using the rfPIC12F675 with the correct frequency band. Then, change the frequency in the previous equations to find your new values for C_1 and C_2. Round off C_2 to the nearest standard value for C4. Find two standard-value capacitors for C5 and C6 that in series make the closest possible match to the calculated C_1. Figure 5 has experimentally verified capacitor values for several commonly used UHF carrier frequencies.

The minimum RF equipment to proceed with testing is a spectrum analyzer and antenna that works from the carrier frequency up to at least its 5^{th} harmonic. In order to see if board changes are improvements, it is important to have a very repeatable environment away from interference. If this is your first RF experience, get some training and then lots of hands-on practice to understand the setup and reduce measurement errors.

The RF circuitry could be enabled by shorting the enable and data lines high or by programming the processor to do it. The code for this application note (located on www.microchip.com) holds the RF output on with no modulation as long as switch SW2 is pressed. Adding modulation makes the antenna tuning unnecessarily more difficult. Once the antenna is tuned, pressing switch SW1 will modulate the data pin. Varying potentiometers R1 and R2 will vary the modulation frequency. Check the source code comments for more details.

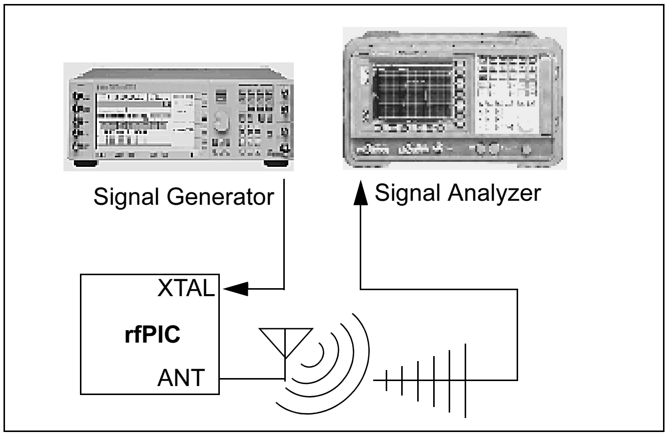
Build up about 5 of the circuit boards to do your design verification. The parts are listed in Figure 6, but do not stuff C4, C5, C6, or R9 yet. The first time you build this circuit it is best to use RF trimmer capacitors to understand how the performance shifts with the capacitor values. One source for quality RF trimmer capacitors is an engineering kit from www.voltronicscorp.com, such as the J series that includes a non-metallic tuning tool.

Use trimmer capacitors with maximum values approx. double the calculated capacitance to get an idea how the capacitance affects performance. Tune the trimmer capacitors for peak output power and see how sensitive they are to slight variations. Note which capacitor is more sensitive and how much changing one cap affects the tuning of the other capacitor

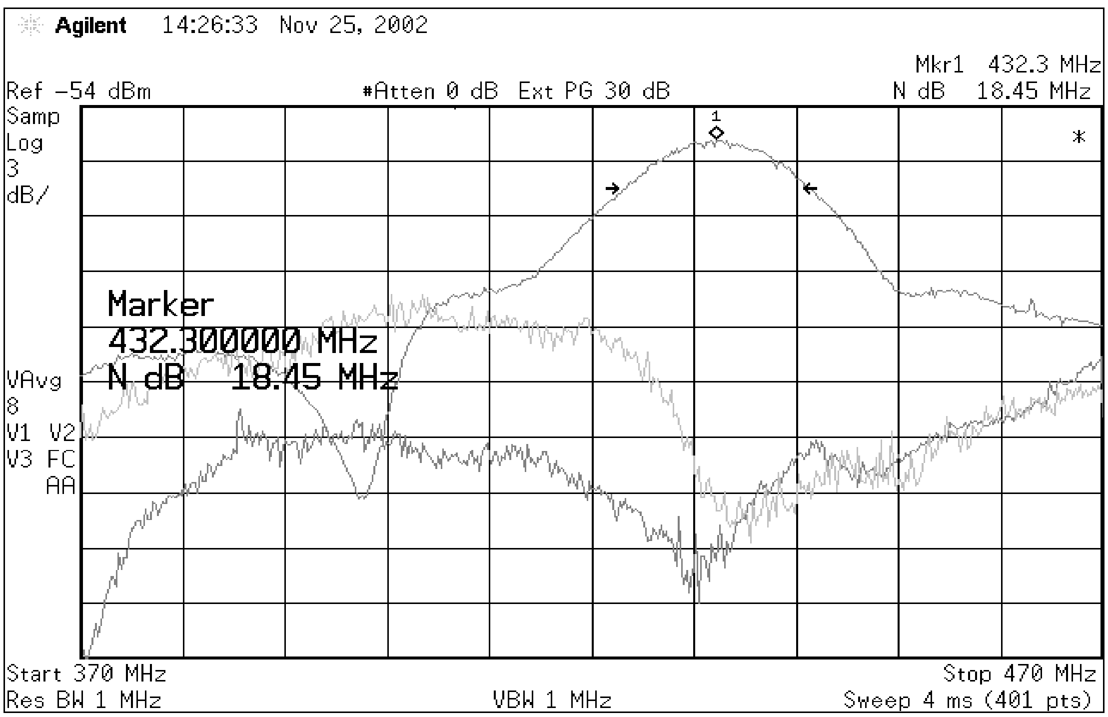
You may notice that even with a good tuning tool the performance shifts when you remove the tool. One way to overcome this problem is to rotate the trimmer through the peak RF power and remember the peak. Then go off to one side of the peak and without changing your hand position, barely lift the tool off the trimmer and see which way the power jumps. If the power jumps away from the peak, then you are on the wrong side of the peak. Rotate the trimmer back through peak power to the other side. With a little practice, you will know how many dB's the power will jump to land right at the peak value. Then, it will be easy to quickly tune the trimmer despite the shift caused by the tuning tool.

FIGURE 7: MEASURING Q OF ANTENNA

A) Setup



B) Spectrum Analyzer Plot



C) Q Calculation

Q = Peak Frequency / 3db Bandwidth

= 433.92 MHz / 11 MHz

= 39

To get a better picture of the tuning process, connect a capacitively-coupled signal generator to the rfPIC instead of the RF crystal. This setup is described in Application Note AN242, "*Matching Small Loop Antennas to rfPIC™ Devices*" and shown in Figure 7. Sweep the frequency about 10% above and below the original crystal frequency. There should be a peak in output power at the loop's resonant frequency. Now tune the trimmer capacitors again and see how each one affects the center frequency and amplitude. Be careful that the leads to the signal generator do not corrupt your results. Keep them short, shielded, and possibly loaded with ferrite beads.

With this setup it is easy to measure the antenna bandwidth. It is the difference between the two frequencies 3 dB down on either side of the peak power. The Q of the antenna is the peak frequency divided by the bandwidth. A good target to simplify manufacturing is to keep Q less than 20. Higher Q antennas will have more output power but may have to be hand tuned to center the resonant frequency on the RF carrier frequency.

Adding series resistance to the antenna trace can reduce the Q of the antenna. Now it is clear why the "unwanted" ESR of the tuning capacitors is acceptable. Recalling from the antenna equations that series resistance can be transformed to parallel resistance, we can instead place the resistance in parallel with the antenna. However, this would create a DC path through the pull-up inductor that would quickly drain the battery. Since power and ground are shorted in AC analysis, the resistor has the same performance if it is placed in parallel with the inductor. Figure 8 shows the effect on Q for several resistor values.

The inductor type and value also has an impact on peak power and harmonic levels. If you choose to experiment and vary the inductance value, you will find that little to no retuning of the antenna is necessary. There will be very little degradation in performance for small inductor value changes so it would be beneficial to change the inductor value to one already stocked by your company.

To lower cost, you can even eliminate the inductor and let the resistor alone bias the power amp output. This will reduce the output power by several dB and extra care must be taken to keep the increased harmonics within limits.

The fastest way to display all the harmonic levels is to configure the spectrum analyzer to segment the frequency axis as shown in Figure 9. Traces for 3 transmitters are given to show the power variation. Each horizontal division represents one harmonic. The divisions are configured with the regulatory resolution bandwidth specific to each frequency. Set the display to maximum hold and slowly rotate your transmitter through every axis. For even more useful results, add the antenna correction factor and regulation max/min limit lines to the display.

FIGURE 8: REDUCING Q WITH R9

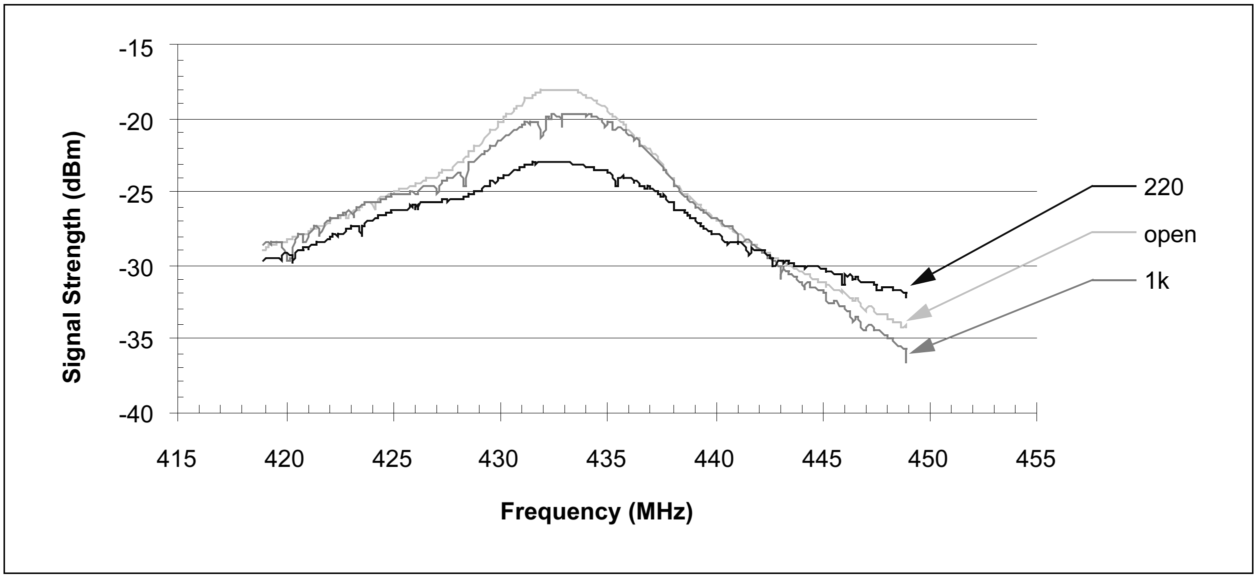
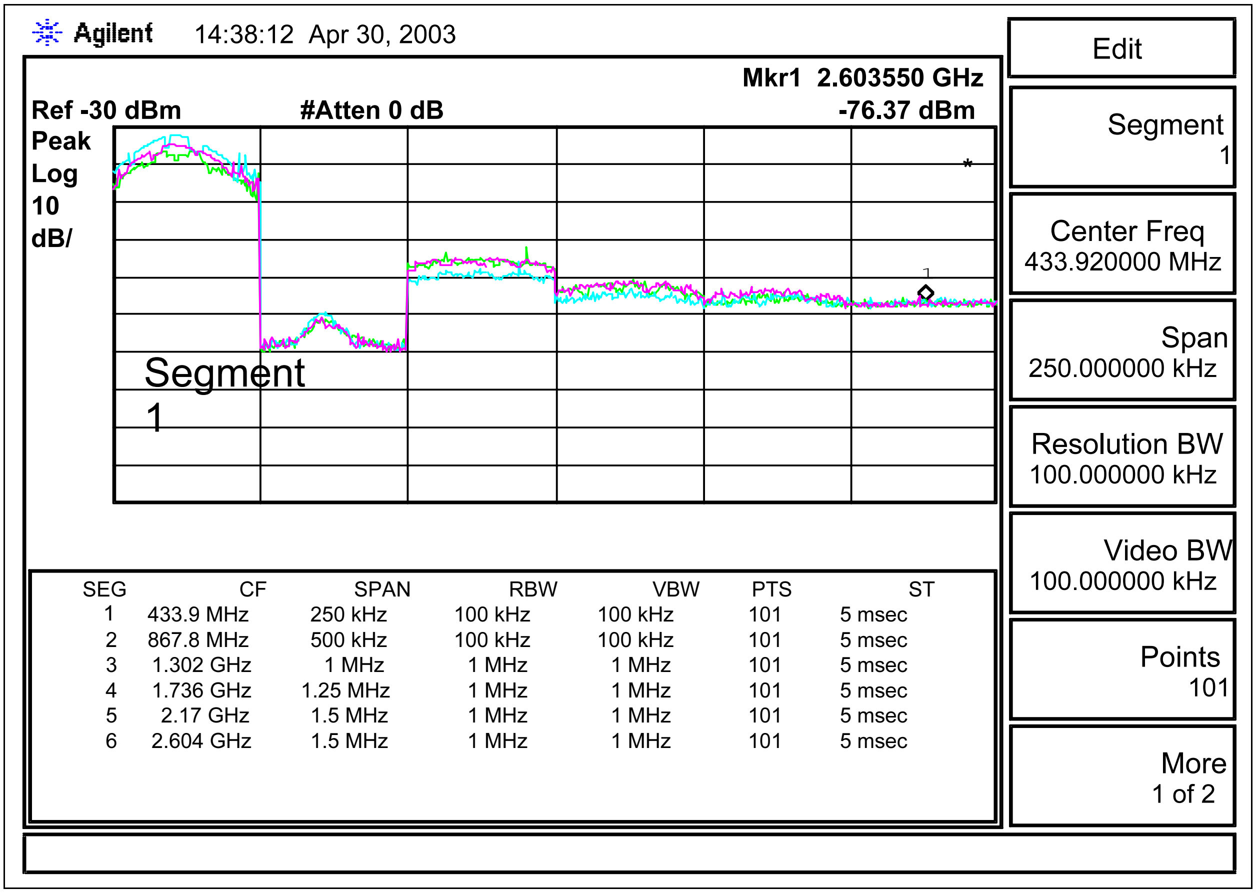


FIGURE 9: SEGMENTED DISPLAY TO CAPTURE PEAK AND HARMONICS



The power amplifier harmonic performance in this design appears to be load dependent. There is a point near maximum output power where the second harmonic level suddenly decreases as the third harmonic increases with C4. Try to tune the C4 capacitance to find the best compromise between the two harmonics that will keep them both below regulatory limits.

Now that the output power is peaked and the harmonics pass regulatory limits, it is time to convert the trimmer capacitors back to fixed values. You could cut the traces to them and measure them on the circuit board with an accurate capacitance meter. Removing them from the board with heat may slightly affect their value but it would preserve the board. Or, you could use your new understanding of the capacitance effect on performance to look at the results and know if the replaced capacitor is too big or too small.

The capacitance meter will probably get you closer than the original calculations but most meters will not measure capacitance, ESR, and parasitic inductance at the RF carrier frequency. Usually, you will still have to do a little fixed capacitor swapping to get the final value. You can probably skip the trimmer capacitors and jump right up to this stage after you get comfortable with your design, the capacitor calculations, and following the fine-tuning procedure.

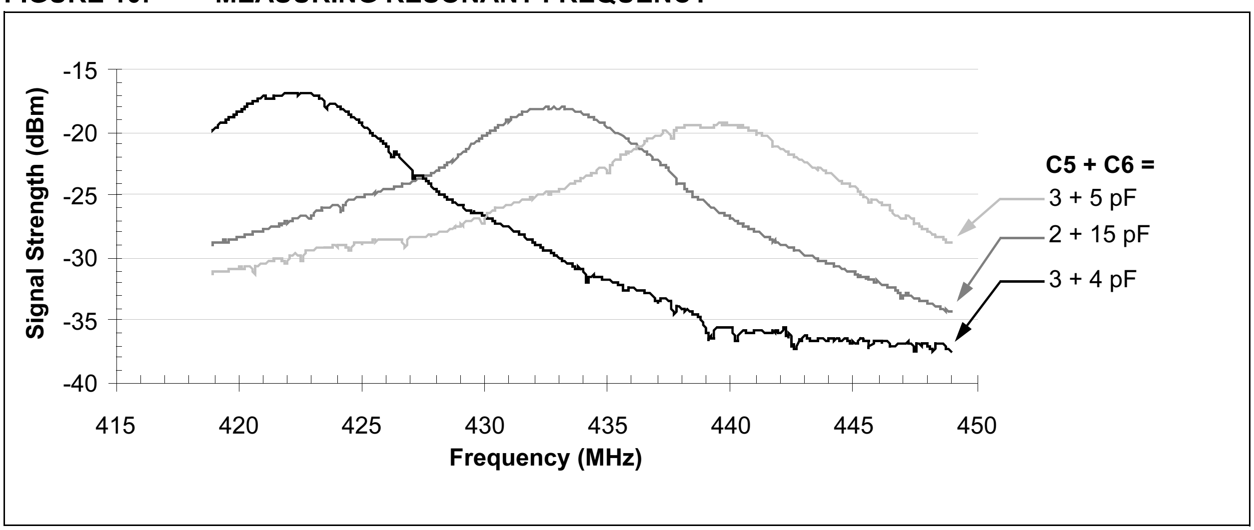
The fine-tuning procedure that I found success with is to place your best-guess value in C4, C5, and C6 and then verify that each component is the optimal value. If possible, sort the components to find parts from the middle of their tolerance distribution.

The easiest way to determine the series combination is to start with C5 set to a standard-value capacitor that is a little bigger than the value calculated for C_1. Then place a much larger capacitor in C6 that will reduce C5 to the calculated value. Using the signal generator, find the frequency that generates the peak output power. If the frequency is too high, reduce C6 until the peak frequency is correct. Increase C6 if the peak frequency is too low. The resonant frequency for several example values is shown in Figure 10.

Measure the output power and then try the next larger and smaller standard values for C4 to determine which direction to search for the best value. Remember to check peak output power and harmonic power levels as C4 is tuned. Once the value for C4 is determined, verify that the peak power frequency is still centered on your RF carrier frequency or adjust C6 accordingly.

Be sure to always let the freshly soldered capacitors and circuit board cool to room temperature before running the tests. Use the time while the solder cools to document everything from component values to fundamental and harmonic power levels. Compare the power levels between tests to make sure that nothing has gone wrong.

FIGURE 10: MEASURING RESONANT FREQUENCY

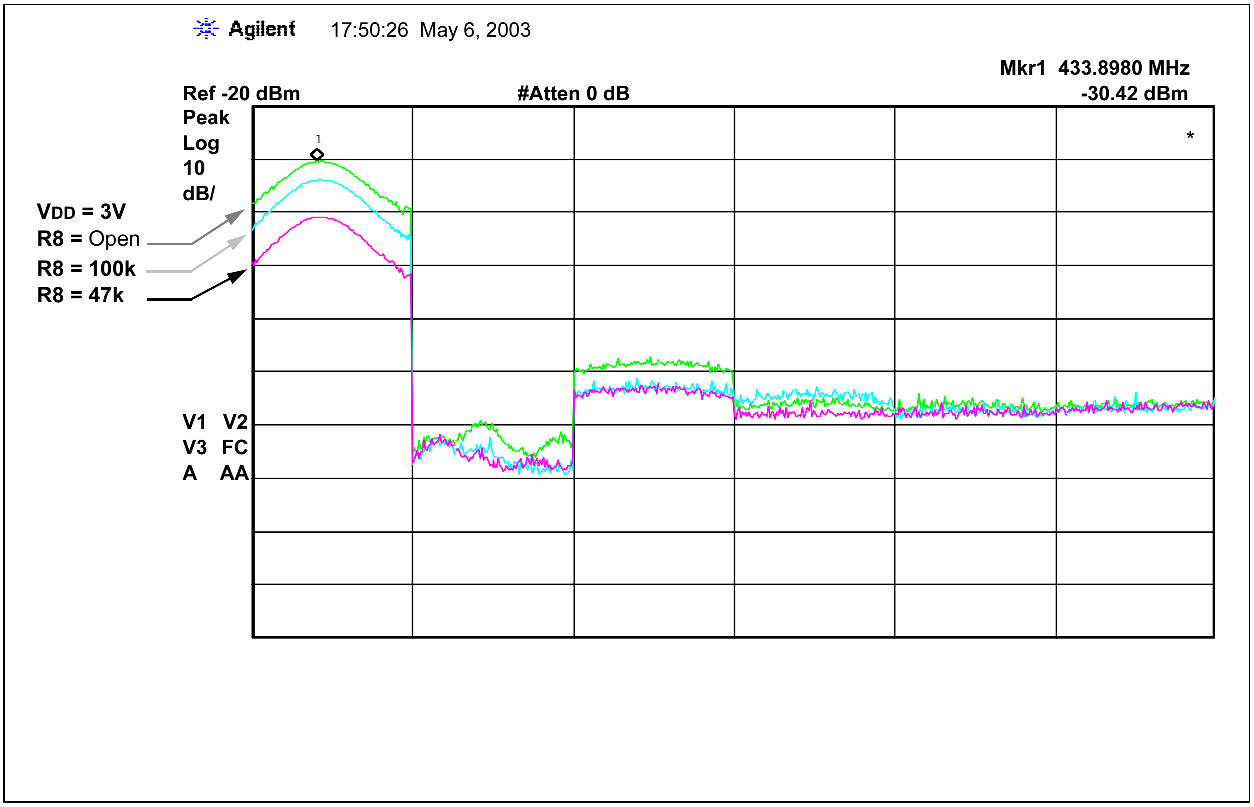


An alternative to soldering is to press the modified capacitor values onto the capacitor pads with a pencil eraser. This permits rapid change of parts, reusing the identical parts, and prevents heating effects. However, it does not work as well for tweaking harmonics down to regulatory levels. The most important concern in both methods is to keep the readings repeatable.

Now, sweep the oscillator to measure the bandwidth of the antenna again. The peak power should be right on your carrier frequency or you will have to go back and retune C5 and C6. If the Q is still above 20, reduce the value of R9 and retest. Make a final check that C4 is still tuned for peak output power. Reducing the Q will probably result in about 5 dB lower output power. If too much output power is lost to make your minimum wireless system reliability/range specification, you may be forced to tune each board in production.

Replace the signal generator with the desired crystal and confirm that it is operating at the correct frequency. A final power and harmonic level test is required to confirm that the signal generator leads were not distorting the readings.

FIGURE 11: REDUCING OUTPUT POWER WITH POWER SELECT REGISTER



5.0 MANUFACTURING TRANSMITTERS

Since each component has tolerances, including the transmitter and circuit board, it is important to build several boards and do some statistical analysis to estimate your production yield. Build as many boards as you can afford with the same component values, but from the normal tolerance distribution. Perform the fundamental and harmonic power level tests on each board. Also confirm that there are no other spurs around the carrier or between harmonics that may be above regulatory limits.

There may be considerable variation between boards for several reasons. The rfPIC transmitter has three types of part-to-part variations that affect the results. The ideal matched load impedance, the strength of the harmonic power level sources, and the power amplifier gain can vary by 3 dB.

In addition, the antenna components will vary. The largest contributor is probably the widest tolerance capacitor, or the capacitor tolerance of the smallest value capacitor. The ESR and parasitic inductance of the capacitors will also vary. The circuit board will have production variability as well as sensitivity to temperature and moisture which may change the loop antenna's resonant frequency and impedance.

Be sure to reduce the affect of temperature by only using C0G dielectric capacitors to tune the antenna. As the battery discharges, it too will have an impact on power levels. In addition, there are long-term aging effects on the crystal frequency and other components.

Some of these variations are specified or characterized but many are not. Your design will be very impressive if 100% of your test boards pass regulatory limits and the peak power of all the boards is within a 6 dB window. Statistically analyze the data to estimate your volume production yield. Analyze the outlier boards to find improvements that can increase production yields.

Regulatory issues can probably be traced back to the C4 capacitor value. Output power variation level issues require replacing the crystal with a signal generator to measure the peak frequency, its power, and the bandwidth. Likely solutions are to increase the bandwidth by reducing R9 or recenter the distribution with a capacitor change. For even tighter distribution, you may need to purchase higher precision components or prescreen the parts.

6.0 POTENTIAL MODIFICATIONS

To reduce the board area the components C3, C4, L1, and R9 could have been rotated 90° and moved closer to the crystal. This would also permit opening up the antenna wider by moving the ground plane edge down. Moving these components with the microcontroller to the right edge of the board would take the kink out of the antenna and reduce its capacitive coupling to the ground plane. It would be interesting to experiment with the self-resonance of C4 to filter off harmonic spurs.

The peak output power is too high for FCC limits, so the transmission needs to be duty-cycled as allowed in FCC rule 15.35c. To transmit higher duty cycles or even continuously under FCC rule 15.231, the peak power must be reduced. Figure 11 shows how the peak power drops as resistance is decreased on the PS pin.

> **Note:** Meeting regulatory limits may be more difficult without the duty cycle advantage since the harmonics do not go down proportionately with the output power.

The ideas from this application note were intended to jump-start your loop antenna design. Hopefully, you are able to implement them quickly and then find ways to improve them.

Associated files in 00868.zip:

- LoopCalc.xls Antenna Equations Calculator
- 00868.asm Microcontroller Source Code
- 00868.hex Executable Code in HEX format
- 00868bom.xls Bill of Materials Spreadsheet
- 00868.top Top Signal Layer
- 00868.bot Bottom Signal Layer
- 00868.tss Top Silk Screen Layer
- 00868.tsm Top Solder Mask Layer
- 00868.bsm Bottom Solder Mask Layer
- 00868fab.pdf PCB Fabrication Drawing
- 00868.drl Drill Coordinates
- 00868.pdf Assembly Drawings

7.0 REFERENCES AND ADDITIONAL INFORMATION

1. Farron Dacus, "*Introducing Loop Antennas for Short-Range Radios, Part 5*" (Microwaves & RF [July 2002] 80-88)
2. Farron Dacus, "*Matching Loop Antennas to Short-Range Radios, Part 6*" (Microwaves & RF [August 2002] 72-84)
3. Myron Loewen, "*Designing an FCC Approved ASK rfPIC Transmitter*". Application Note AN242
4. Jan van Niekerk, "*Matching Small Loop Antennas to rfPIC™ Devices*". Application Note AN831
5. K. Fujimoto, A. Henderson, K. Hirasawa, and J.R. James, "*Small Antennas*". Research Studies Press Ltd. John Wiley & Sons, 1987
6. Frederick Grover, "*Inductance Calculations Working Formulas and Tables*". Dover Publications, 1946
7. K. Fujimoto and J.R. Handbook, "*Mobile Antenna Systems Handbook*, *Second Edition*". Artech House, 2001

NOTES:

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Microchip received QS-9000 quality system certification for its worldwide headquarters, design and wafer fabrication facilities in Chandler and Tempe, Arizona in July 1999 and Mountain View, California in March 2002. The Company’s quality system processes and procedures are QS-9000 compliant for its PICmicro® 8-bit MCUs, KEELOQ® code hopping devices, Serial EEPROMs, microperipherals, non-volatile memory and analog products. In addition, Microchip’s quality system for the design and manufacture of development systems is ISO 9001 certified.

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05/30/03