Designing an EMC-compliant UHF oscillator

This straightforward design technique for two-port SAW oscillators minimizes stability problems and time-consuming experimentation.

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Before jumping right in and discussing oscillator design it would be prudent to review the fundamentals of two-port surface acoustic wave (SAW) devices.

The two ports being referred to are the input port and an output port. A typical two-port SAW is a three-pin device. There is a pin for the input signal and a pin for the output signal. The third pin serves as the common node for the input and output ports and is tied to the case of the device. The physics of SAW devices is based on the phenomenon of piezoelectricity.

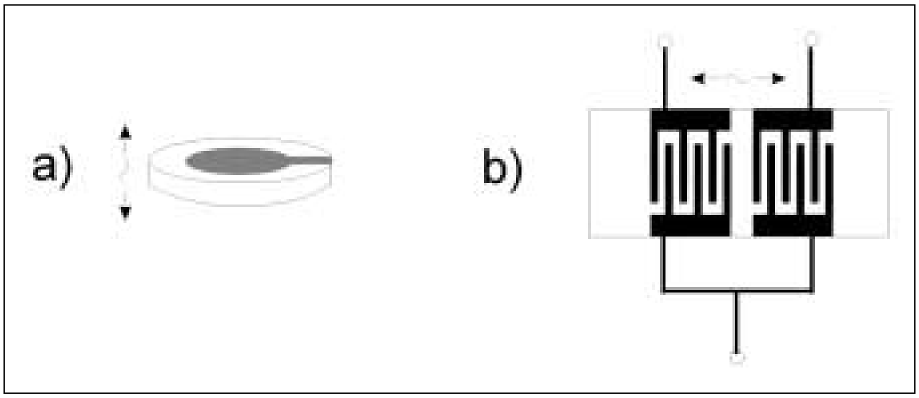

Figure 1. a) Perspective view of a standard quartz crystal resonator. Circular electrodes are placed on top and bottom of a quartz disk, allowing for a resonant standing wave to occur. b) Top view of a 180 degree, 2-port SAW resonator (For simplicity, reflector electrodes are not shown).

Piezoelectric materials exhibit a coupling between acoustic and electrical properties. In other words, an electric field causes a mechanical strain and vice versa. In the same manner, applying an AC electric signal to a piezoelectric material causes acoustic waves or vibrations. Various types of crystal exhibit piezoelectricity; however, quartz is typically used because of its stability and ease of manufacturing. Quartz crystals, commonly used through the VHF frequency region of the spectrum, are based on thin disks of quartz with electrodes placed at the top and bottom. This geometry sets up an acoustic wave in the disk, with the resonant frequency being inversely proportional to the thickness of the disk. Such crystal devices become impractical at high frequencies because the disks required become too thin.

SAW devices are similar to standard quartz crystals; however, they rely on surface acoustic waves. SAWs are similar to ocean waves in that the wave energy travels along the surface of the material. For two-port SAW devices, a pair of interdigitated (IDT) metal fingers are placed on the quartz surface and used to excite a surface acoustic wave. The resonant frequency of a SAW device is inversely proportional to the spacing of the interdigitated fingers. Since the electrode fingers can be deposited using state of the art IC deposition technology, small spacings and high frequencies (into the GHz range) can be achieved. SAW resonators also have high quality factors (Q's). The unloaded Q of two-port SAWs typically falls in the range of 5,000 to 20,000.

A two-port SAW resonator can be modeled with an RLC circuit, as shown in Figure 2. The resistor, R_m, represents the energy loss in the resonator. C_o represents the inter-electrode capacitance. C_m and L_m simulate the resonant characteristics of the device. The transformer is an ideal one-to-one transformer, with the secondary winding inverted so as to model a constant 180 degrees of phase shift. It is important to know that this equivalent circuit is only valid in the region around resonance. An actual SAW resonator has a more complicated response that includes sidelobes and harmonics. Figures 3 and 4 compare the transmission characteristics of the model to an actual RP1239 device used as the physical reference for this technique. Figure 3 shows that, in the neighborhood of resonance (±0.2 MHz), the lumped element model is accurate. Figure 4 shows that, for a broader frequency span (±3.0 MHz), the lumped element model is inadequate.

Oscillator fundamentals

There exist two common methods for oscillator analysis and design, the feedback/loop method and the negative resistance method[2][3]. Although either method can be used to analyze any circuit, oscillators using two-port devices such as SAW resonators and SAW delay lines are most amenable to the loop method. Following the loop method, the two-port SAW is placed as an element in the feedback loop of an amplifier, as shown in Figure 5. The figure shows the oscillator in open loop configuration; i.e. the feedback loop is cut to provide input and output ports.

When the loop is closed, the circuit will oscillate if the following two conditions are met:

1) The first condition for oscillation is that the net gain through the loop must be one or higher. In decibels, this translates to a gain of at least 0 dB.

2) The second condition is that the phase shift in the loop must total 0°.

When these two conditions are met, positive feedback will occur at the resonant frequency, resulting in oscillation.

The resonant frequency will be in the neighborhood of the resonant frequency of the SAW device. A popular misconception about oscillators is that the oscillation frequency is determined by the resonant peak. Actually, the exact frequency of resonance is determined by the point of 0° total phase shift. Figure 6 illustrates this concept. This figure shows the transfer function of a hypothetical open loop 315 MHz oscillator circuit with the topology of Figure 5. While the peak of the gain occurs at 315 MHz, the zero phase location occurs at about 314.98 MHz. The gain at 314.98 MHz is approximately 5.75 dB. Both criteria for oscillation are met at this frequency. Therefore, this circuit will oscillate at 314.98 MHz.

The zero phase shift frequency defines the resonant frequency; however, any real-world oscillator circuit will have noise, or variation, about the resonant frequency. The variance of the noise about the center frequency is related to the quality factor, or Q, of the oscillator, with higher Q's producing smaller frequency noise. Noise in the loop, summed with the energy from power-on transients, provides the energy to start oscillation when the circuit is powered. Since a higher Q results in smaller noise, a circuit with a high Q will take longer to start up than a similar circuit with a lower Q. When there exists more than one frequency where the oscillation conditions are met, oscillation becomes difficult to predict. The circuit may oscillate at one of the frequencies or it may hop between several frequencies. Circuits with more than one such frequency must be avoided.

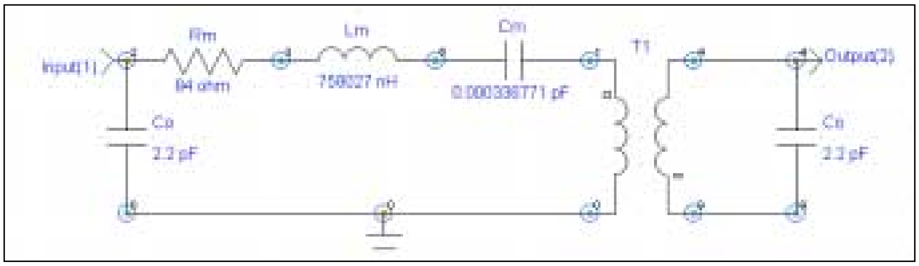

Figure 2. Lumped element model for a 180° two-port SAW resonator. Values are given for a RF Monolithics 315 MHz device.

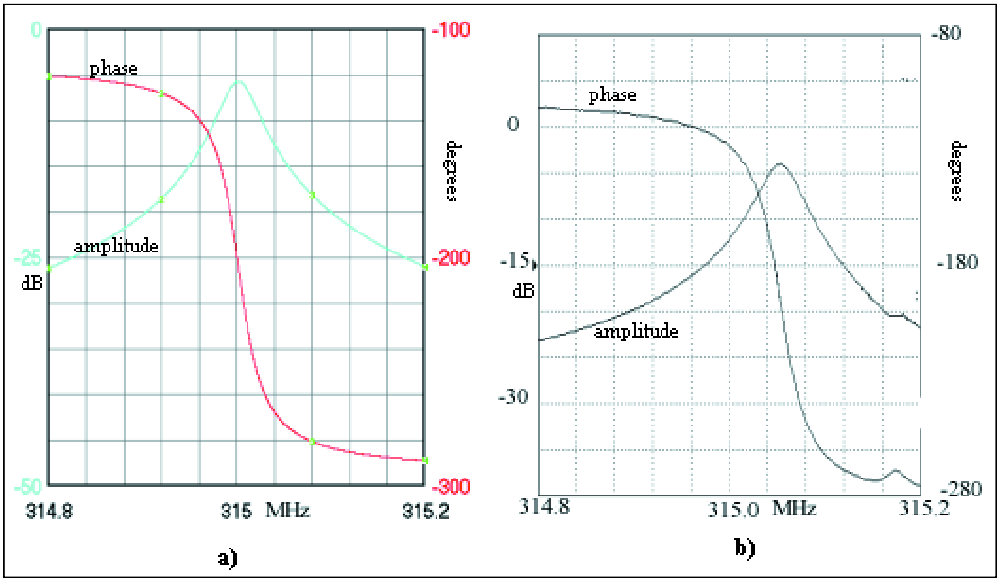

Figure 3. SAW response (S_{21} parameter) in neighborhood of resonance for a 315 MHz SAW oscillator: a) frequency response (model). b) frequency response (measured with network analyzer).

The power supply voltage, the net gain through the loop, and the compression characteristics of the amplifier together determine the amplitude of oscillation. At the onset of oscillation, the signal is at a low voltage; with the amplifier operating in the linear, or constant gain, region. Positive feedback causes the amplitude of oscillation to increase until the amplifier output starts to saturate. At saturation, the amplifier gain decreases and tends to zero as the power supply voltage is approached. The quiescent point of the amplitude of oscillation is the point in the compression region where the amplifier gain equals the losses through the feedback loop. Consequently, unless the linear gain of the amplifier equals the losses through the loop, the amplifier will be operating in the non-linear region for portions of the oscillation cycle. This non-linearity of gain distorts the waveform, producing harmonics of the fundamental frequency. Thus a side effect of a high gain margin is a signal with high harmonic energy content. The harmonics can be reduced by reducing the loop gain or by filtering the oscillator output.

Design method

Typically, oscillator design is as much an art as it is a science. However, by designing the oscillator in stages using empirical and analytical methods where appropriate, much of the trial and error typically encountered can be avoided. In our design process, a combination of physical circuit measurements and simulation techniques was used, utilizing simulation for filter synthesis and lab measurements for determining loop gain/phase.

The basic topology of the SAW oscillator design is shown in Figure 7. It is a feedback network with the loop consisting of an attenuation network, an RF amplifier, a SAW device, a frequency selective filter, and a phase shift filter. The signal is output through a coupling network. Of the five blocks in the feedback loop, only the RF amp and SAW device are absolutely required. The frequency selective filter is only necessary if there are spurious resonances; i.e. unintended frequencies where the oscillation criteria are met. The attenuation network is only needed if there is too much loop gain and a more linear output response is needed. The phase shift filter is most likely needed, since it is used to set the location of resonance. In addition, a two-port SAW provides only 180 degrees of phase shift. So there is a 50/50 chance that the circuit will not oscillate without the proper phase shifting.

RFIC amplifier selection

At the core of any oscillator is an amplifier to provide gain. Two common choices for amplification are RF transistors and RF integrated circuits (RFICs). An RFIC was chosen because of the relative design simplicity. Other attractive features common to RFIC amplifiers are a broad frequency bandwidth and a nominal 50 Ω input and output impedance. Furthermore, with the present state of IC packaging, an RFIC will typically have a layout footprint comparable in size to that of a transistor.

Gain is the most important criterion for selecting the amplifier. The amplifier must have enough gain at the desired oscillation frequency, and this gain must be large enough to compensate for any losses that occur in the feedback loop. To ensure reliable and rapid oscillator startup, a gain margin above 0 dB is included. A typical value used for gain margin is 6 dB.

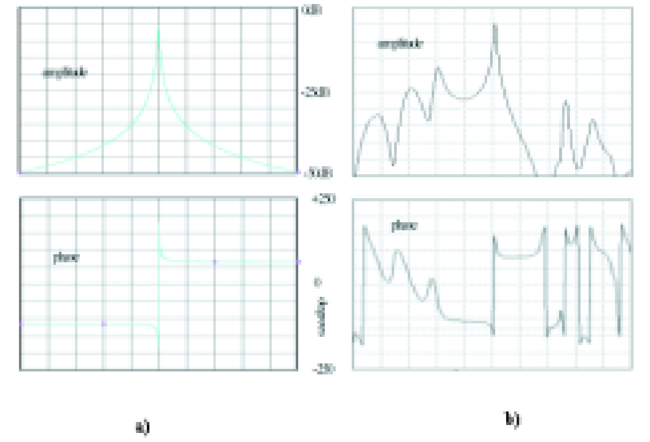

Figure 4. SAW response (S21 parameter) in broader frequency range for a 315 MHz SAW oscillator the device: a) SAW frequency response (model). b) SAW frequency response (measured with network analyzer).

Maximum input power is another criterion important for oscillator design, especially when using amplifiers with high gain. Some RFIC amplifiers can only tolerate low input power without damage occurring to the amplifier. For oscillator design, where the output is fed through a feedback network and then into the input, the following condition can be followed to avoid device damage: $P_{MAX,\ input} \geq P_{MAX,\ output} - P_{loop}$, where P_{MAX}, input is the maximum input power, P_{MAX}, output is the maximum output power, and P_{loop} is the loss through the feedback network, each expressed in dB.

Gain/phase vs. frequency characteristics

The next step in the design process is to build an open loop circuit with the amplifier in series with a SAW device so that the gain versus frequency behavior can be determined. To avoid oscillation at spurious frequencies, a low-pass or band-pass filter may need to be placed in line with the SAW device. The gain and phase of the circuit as a function of frequency is measured using a network analyzer to determine the location of any spurious resonant frequencies.

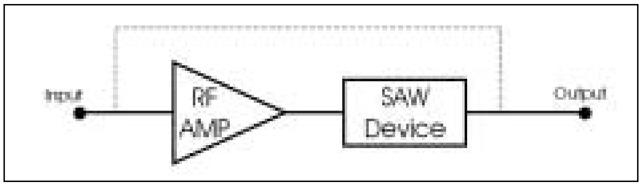

Figure 5. Block diagram of a two-port SAW oscillator in open configuration. The dotted line shows the closed loop.

From this, the requirements of the frequency selective filter can be determined.

Phase compensation

After a frequency selective filter is designed, the entire open loop circuit shown in Figure 8 is implemented. The gain and phase behaviors, as a function of frequency, are measured again. It is important to measure the phase of the loop with the amplifier in saturation because an amplifier's phase curve is different in saturation from that of linear operation. S-parameters provided by the manufacturer should not be relied upon because this data is measured in the linear regime. The phase can be measured using a network analyzer, or determined via RF simulation. When conducting measurements, the phase shift of the probes or connectors must be calibrated out to achieve accurate results.

For the oscillator to function as intended, the loop phase must be adjusted so that it equals 0° at the desired resonant frequency. For two-port resonator SAW devices, the phase changes by about 180° near resonance. Because of the phase shifts caused by device parasitics, transmission lines between components, the amplifier, and any other components in the loop, a point of 0° phase may not occur in the neighborhood of resonance. The resulting circuit may not oscillate reliably unless the loop phase is properly adjusted. Even if the circuit does oscillate, it may not be at the exact desired frequency.

Once the optimal frequency is determined, the phase, ϕ, through the loop at this frequency is measured with a network analyzer or through simulation. The desired phase for the phase shifting filter is simply $\theta = -\phi$, so that the total phase sums to 0° at the optimal frequency.

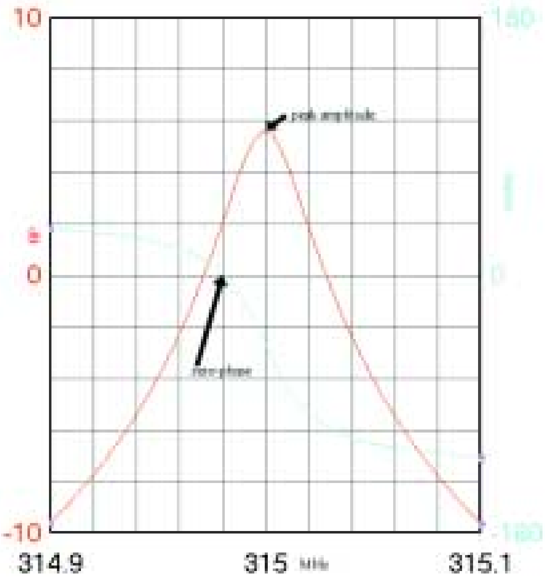

Figure 6. Open loop transfer function (S_{21} parameter) of a 315MHz SAW Oscillator. The gain [dB] is shown in red. The phase [degrees] is shown in blue.

An alternate method can be employed to determine the phase shift. The loop can be closed with a variable-length transmission line. The length of the transmission line is varied until the circuit oscillates at the desired frequency. The equivalent phase shift is determined from this optimal length using the relation:

$$\theta = -\frac{L}{\lambda eff} \bullet 360^{\circ}$$

where L is the length of the transmission line and λ_{eff} is the effective wavelength of resonance on the given transmission line. Two parallel 50 Ω terminated microstrip lines can be used to create a variable length transmission line. A copper short can be placed at any point across these parallel transmission lines to give arbitrary lengths.

The next step is to design a filter to produce the desired phase shift. The common design practice for designing such a filter is to use an empirical trial and error tuning method. However, a purely analytical method can be applied. Utilizing Butterworth filter coefficients, a Matlab program was created that calculates the capacitor and inductor values based on the input phase shift, operating frequency, and the desired filter topology, pi or tee. The calculated, normalized values are then converted to a characteristic impedance of Z = 50 Ω, using the formulas given in[1]. This method of phase shifting is based on the fact that Butterworth filters possess a linear phase versus frequency relationship in the pass band. The slope of this linear relationship is negative for a low-pass filter and positive for a high-pass filter:

Low-pass Butterworth Filter:

$$\theta = (f) = -n \bullet \frac{f}{f_C} \bullet 45^{\circ}$$

High-pass Butterworth Filter:

$$\theta = (f) = +n \bullet \frac{f}{f_C} \bullet 45^{\circ}$$

where n is the number of poles, f_c is the corner frequency and θ is the phase,

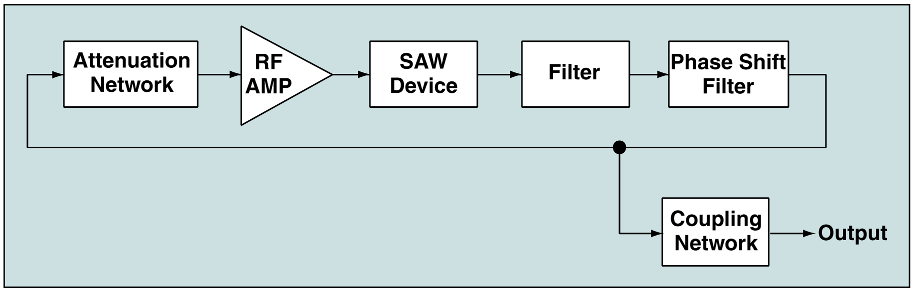

Figure 7. Oscillator block diagram.

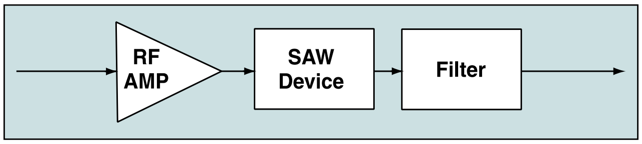

Figure 8. Open loop oscillator circuit.

given in degrees. Using the above relations, a filter of any desired phase shift at a given frequency can be designed. The first step of the algorithm is to calculate the number of poles required by determining the next highest integer of the function:

$$n = \left| \frac{\theta}{45^{\circ}} \right|$$

The next step is to determine whether a high-pass or low-pass filter will be used, based on the sign of the angle θ and to calculate the filter corner frequency f_c:

$$\theta \le 0 \Rightarrow \text{low-pass filter}, \ f_C = \frac{2\pi f (n \bullet 45)}{|\theta|}$$

$$\theta \ge 0 \Rightarrow \text{high-pass filter}, \ f_C = \frac{2\pi f |\theta|}{(n \bullet 45)}$$

where f is the desired frequency of oscillation. The last step is to use Butterworth filter tables to determine the components (inductor and capacitors) of the filter. The resulting filter will produce a phase shift of θ at the desired frequency (f).

Complete oscillator circuit

To complete the oscillator circuit, the phase shift filter is added in series with the feedback loop. When the open loop response is measured, the phase should be 0° at the desired oscillation frequency. When the loop is closed, the circuit will oscillate at the desired frequency. The output of the oscillator is coupled to the loop using an RF power divider, directional coupler, or using a discrete capacitor or inductor. Though capacitors are commonly used to couple AC signals, in this case an inductor is often preferable because it will limit the power of the harmonics. A capacitor, on the other hand, will enhance the harmonic power over the fundamental power since the impedance of a capacitor is inversely proportional to frequency. Another consideration for output coupling is the placement of the coupling network. By placing the coupling network after the SAW and filters, much of the harmonic content from the saturated amplifier will be suppressed.

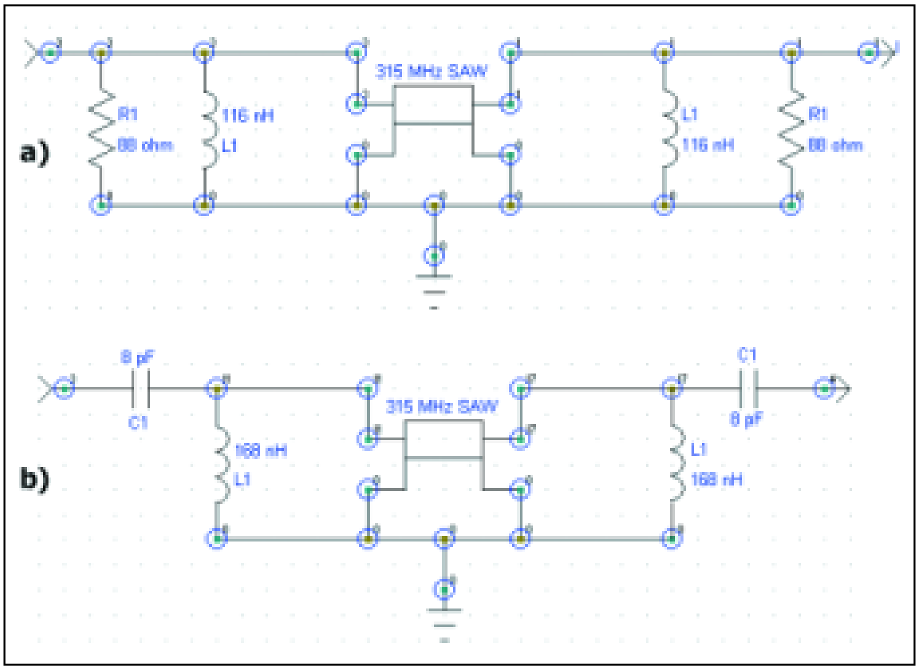

Figure 9. a) RL matching network for a 315 MHz SAW. b) LC matching network for a 315 MHz SAW.

Impedance matching

Referring to the circuit model of Figure 2, it is readily seen that a SAW will not have a 50 Ω impedance at its ports. When connecting a SAW to a 50 Ω transmission line, the consequent impedance mismatch causes insertion loss. Using the model of a 315 MHz SAW, we designed two matching networks and evaluated the results. The first network, shown in figure 9a consists of a shunt inductor and resistor at each port. The inductor, L_1, acts to create a parallel resonance with the SAW capacitance, C_o, effectively canceling out the effects of C_o at 315 MHz. Furthermore, the SAW inductance and capacitance form a series-resonant circuit. The remaining impedance is the series resistance, R_m. The matching R_1 resistors form a pi network with R_m, and provide a 50 Ω input at each port. The matched circuit eliminates reflections at the expense of power lost in the added resistors. This circuit actually has about 5.5 dB of more loss when compared to the unmatched SAW. The one benefit of the circuit is

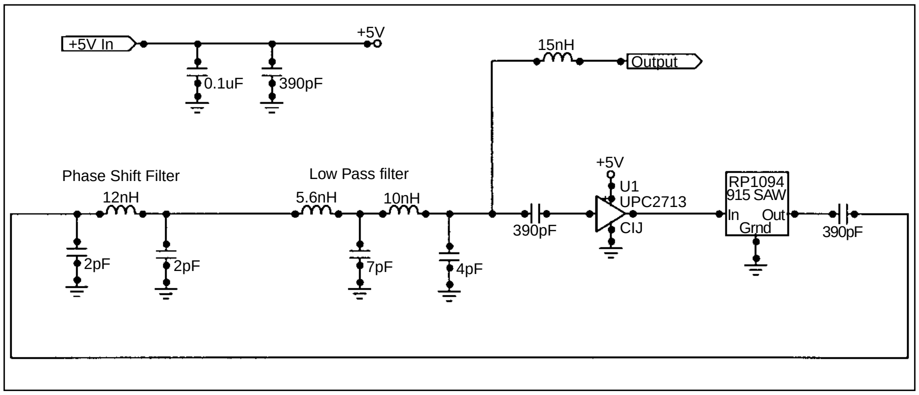

Figure 10. 915 MHz SAW oscillator schematic.

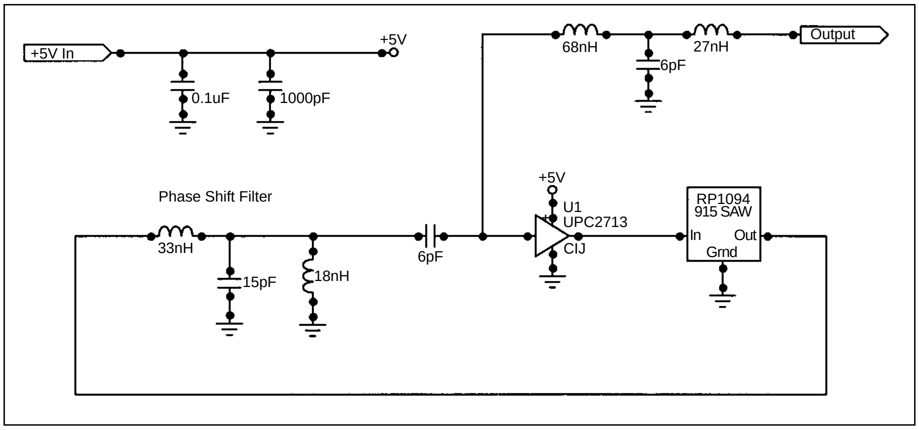

Figure 11. 315 MHz SAW oscillator schematic.

that it creates a slightly higher Q (The in-circuit Q was about 6% higher than the unmatched SAW).

The second matching network is shown in Figure 9b. It consists of an LC network placed at each port, which provides the 50 Ω matching. This circuit reduces the loss by about 3 dB, but reduces the in-circuit Q by about 50%. Because of the dramatic decrease in Q, this matching circuit is not desirable for an oscillator application.

In summary, because impedance matching is primarily a technique to reduce insertion loss, the application of impedance matching to SAW oscillators provides either little benefits to or actually decreases the oscillator performance.

Results

Using the methods described in this paper, two different oscillators were designed. The oscillators exhibited stable frequency response (±50 ppb typical noise over five minute span). Measurements were performed using a HP4396B Network/Spectrum Analyzer. The complete oscillator circuits for a 915 MHz oscillator and a 315 MHz are shown in Figures 10 and 11. For both oscillators, the NEC UPC2713 amplifier was chosen because it has considerable gain in the UHF band. RF Monolithics two-port, 180° SAW devices were selected. All components were surface mount devices, except for the SAWs.

Circuit board layout considerations

The first consideration when performing the board layout is to deter-

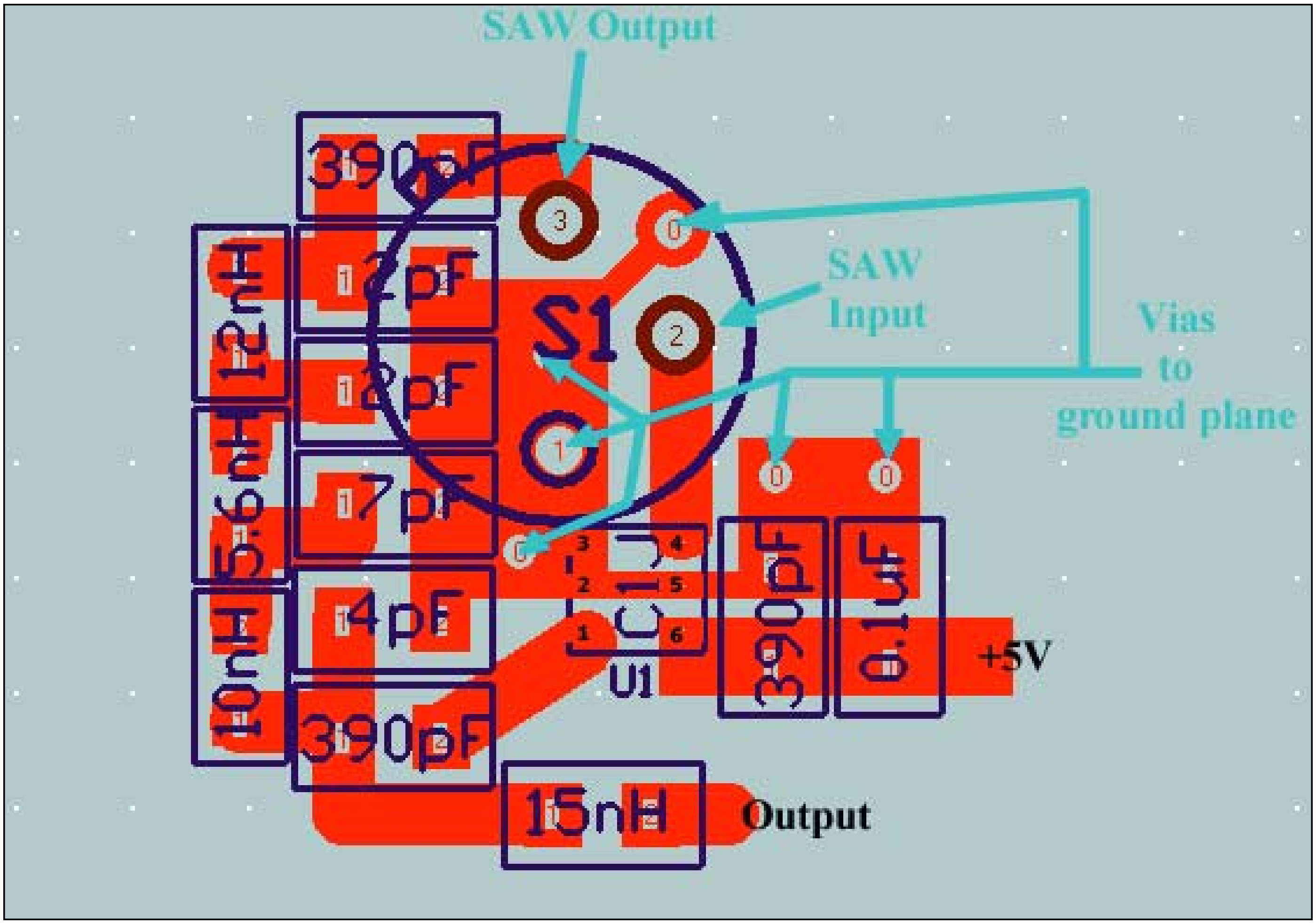

Figure 12. 915 MHz SAW oscillator layout (3X magnification, actual size is 1.75cm x 1.75cm).

mine the characteristic impedance of the printed circuit board (PCB) traces. To reduce reflections, all traces carrying RF signals were designed to a characteristic impedance of 50 Ω. We used 30 mil (0.76 mm) thick PCBs with FR4 dielectric. The PCBs were a double layer with signal traces on top and a solid ground plane on the bottom. Through theoretical analysis and lab measurements, 50 Ω characteristic impedance was determined to correspond to 55 mil (1.40 mm) width traces. Therefore, 55 mil traces were used for all of the RF interconnections. Vias were placed wherever possible for sufficient grounding. The technique of using multiple vias helps reduce effects of interference and noise by providing low-impedance connections to the ground plane. De-coupling capacitors were added to the power supply voltage to prevent RF signals from coupling to the supply. Since the amplifier acts as a variable load at the frequency of oscillation, values of decoupling capacitance were chosen so that the frequency of interest was shunted to ground on the supplies. These capacitors as well as the coupling capacitors on the amplifier input/output were chosen such that they had an impedance of about 1 Ω at the oscillation frequency.

One of the most important things to remember in RF layout is to minimize the diameter of the loops that are formed by each signal trace and its return path. It is important to realize that currents travel in a much different manner at RF frequencies. RF signals follow the path of least impedance, implying that inductance should be limited in all ground paths. The path of least inductance for RF return current is to travel directly below the signal trace, forming the smallest loop diameter for the total current path. At RF frequencies, all the return current on the ground plane will be concentrated directly below the trace and follow underneath the trace wherever it proceeds. Forcing the return current to flow otherwise creates inductance and stray fields. Keeping the overall currents loops small in diameter reduces stray fields, limiting interference and noise susceptibility. Figure 12 shows the layout for the 915 MHz oscillator whose schematic is shown in Figure 10.

It is evident from Figure 12 that the signal paths were kept short and grounding vias were added wherever possible. The SAW resonator (the circle near the top of the figure) is soldered on the backside of the board while all of the electronics are placed on the topside. The device labeled “CIJ” is the RFIC amplifier, with pin 1 at the lower left and pin 6 at the lower right. Notice that the input (pin 1) and output (pin 4) signals to the amplifier are closely accompanied by ground vias so that the return current for the signal can leave the ground pins (pins 2, 3, and 5) of the IC and immediately travel to the ground underneath the signal trace. The same practice was utilized for the inputs and outputs of the SAW resonator.

Conclusion

A methodology for designing two-port SAW oscillators was described, including a general overview of oscillators. Using this methodology, two oscillators were designed, at frequencies of 315 MHz and 915 MHz. By utilizing a combination of open loop measurement techniques and analytical filter design, most of the trial and error process that typically accompanies oscillator design was avoided. The resulting oscillators were robust and stable.

RF

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