RF360 Europe GmbH

A Qualcomm – TDK Joint Venture

Application Note SAW-Components

Design-guide for the SAW oscillator Optimisation for best frequency stability, fast start up time and ghost-less working

App. Note #25

Abstract:

Basic relations between the SAWR´s group-delay, it´s loaded Q-factor and the oscillator´s start up time are presented. Based on this, an optimum frequency adjustment of the SAW oscillator is given to provide best frequency stability.
The dynamic oscillator´s start up scenario is described together with the generation of objectionable ghost spurious. A detailed calculation of the SAWR´s frequency shift over temperature is added in the Appendix.

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SAW oscillator, optimised for best frequency stability, fast start up and ghost-less working

Typical SAW Oscillator is a Colpitts oscillator with grounded base. The base grounding is done by the SAW resonator. Please note the SAW resonator R851 used as an example is obsolete already. The oscillator adjustment theory discussed in this paper, however is valid for any actual EPCOS SAW resonator released for mass production.

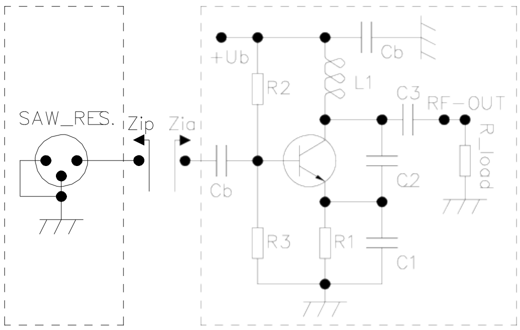
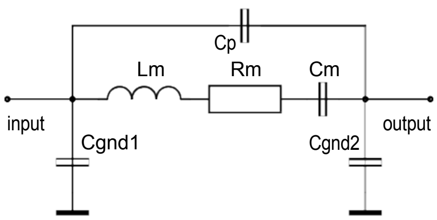


Fig.1: Colpitts oscillator, divided into passive and active network



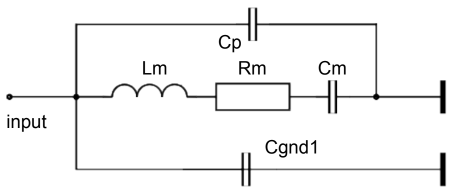


Fig.2a: Equivalent circuit of a one-port SAWR Fig.2b: one-port SAWR, used in a Colpitz oscillator
Lm = motional inductance Rm = motional resistor Cm = motional capacitance
Cgnd1, Cgnd2 describe mainly the housing capacitance, Cp the internal IDT capacitance

In the Colpitts oscillator, the one resonator output port is connected to GND, the input port to the transistor´s base. The SAWR works in a 1-port configuration.
The Q-factor of the SAWR is in a maximum close to the serial resonance frequency of the SAWR. (Loaded) Q-factor is proportional to the group delay of the SAWR in S11 (one-port configuration) or of S21 (two port configuration).

Calculation of Q_{loaded} for a SAW resonator in 2-port configuration

$$Ql = \frac{Qu * Rm}{Rm + Rs + Rl} \qquad IL_{db} = 20 * \log_{10}\left(\frac{Rs + Rl}{Rm + Rs + Rl}\right)$$

$$Q_{loaded} = -\frac{\omega}{2} * \frac{\delta\varphi}{\delta\omega} \qquad Q_{loaded} = \frac{\omega * GD}{2}$$

Fig. 3: Calculating the Q_{loaded} and $Q_{unloaded}$ of a 1-port SAWR in 2-port configuration

Makeing the correlation between the different configurations (2-port configuration and 1-port configuration) of a 1-port SAW Resonator more clear, we set up an simulation based on the electrical equivalent circuit of the EPCOS SAWR R851.

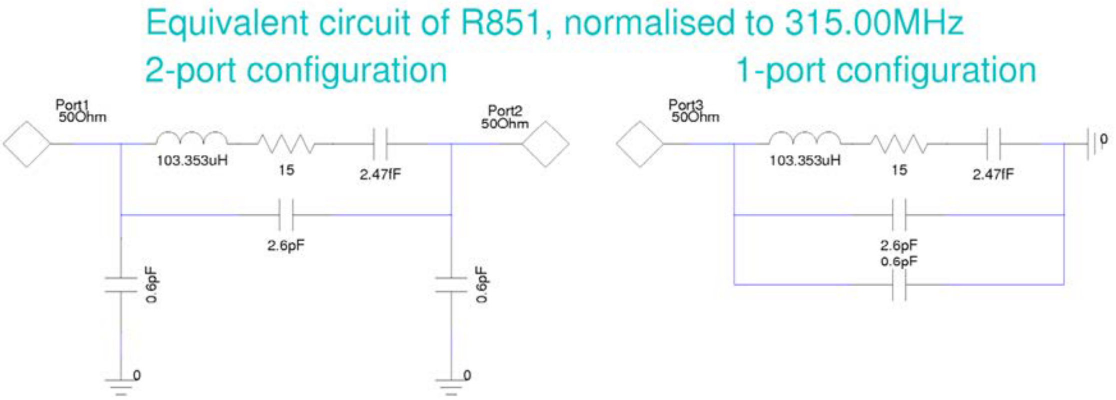


Fig. 4: 2-port and 1-port configuration of SAW Resonator R851

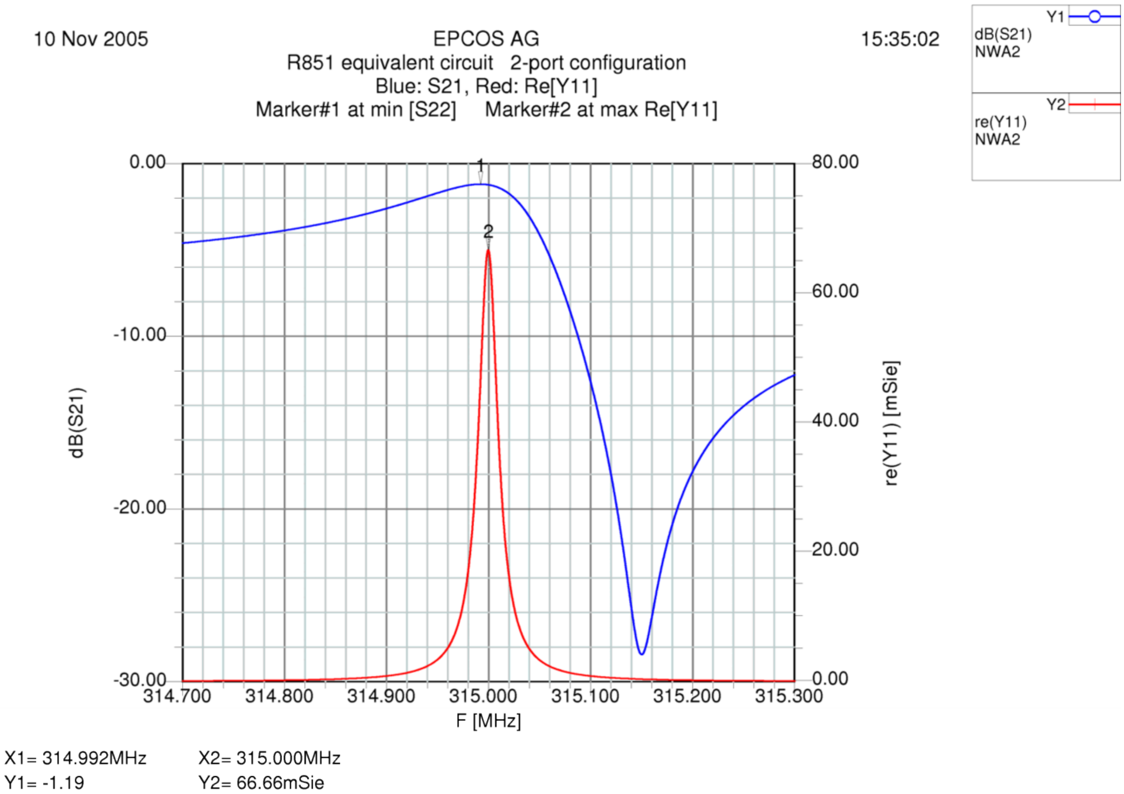


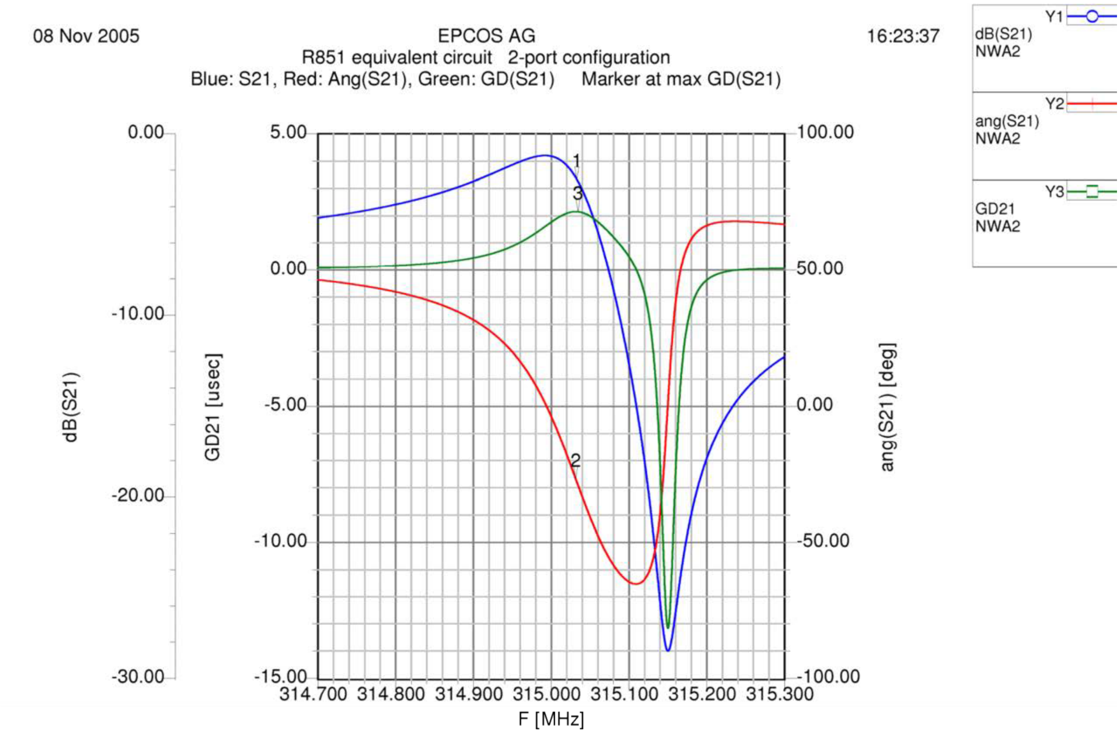
Fig. 5: R851 in 2-port configuration: S21 and Re[Y11]

Y11 – input admittance of a 2-port - is defined with a SHORT placed exactly at the output port #2.
Electrically, Y11 of a 2-port is identical with Y11 of a 1-port.

Y11 = Re[Y11] + Im[Y11]

whereas Re[Y11] is defined by Lm, Rm and Cm, Im[Y11] by C0 // Cgnd1

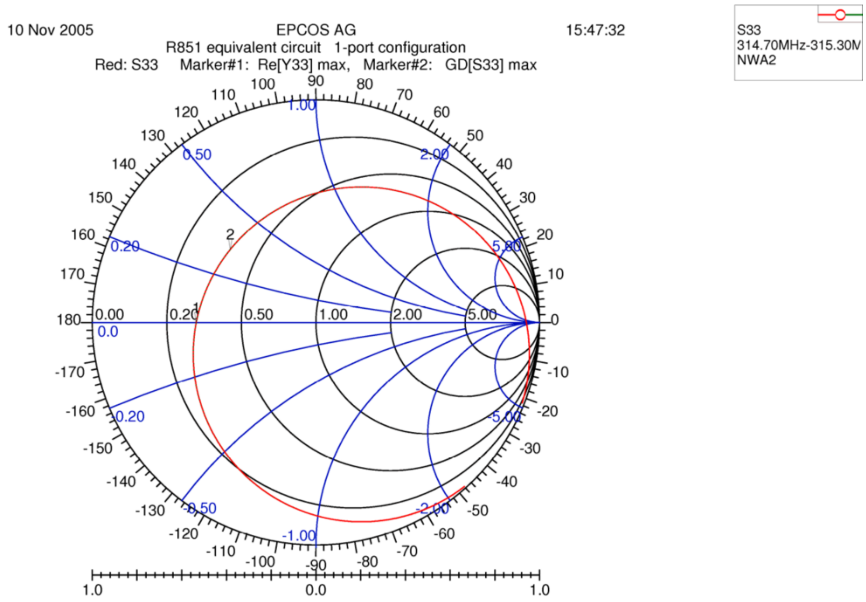
At EPCOS production test field area we measure / calculate Y11 and use the maximum of Re[Y11] to determine the SAWR´s centre frequency. Doing this job, a vector networkanalysator is mandatory.
Between Re[Y11] maximum and the S21 minimum there are about 8kHz (ref. Fig.5, @ R851). Characterising the SAWR´s centre frequency by searching the minimum of S21 is critical because of the extreme flatness of the S21 curve. The result for the SAWR´s centre frequency based on the “minimum of S21 measurement” is often not correct



X1= 315.033MHz X2= 315.032MHz X3= 315.035MHz
Y1= -2.50 Y2= -26.48deg Y3= 2.15usec

Fig. 6: R851 in 2-port configuration: S21, ang[S21] and GD[S21]

To make the whole picture we add S21, ang[S21] and GD[S21]. In the 2-port configuration of the 1-port SAWR, GD[S21] maximum is about 33kHz up from the point of minimum S21.
For a Colpitz oscillator with grounded base, the 1-port configuration of a SAWR is more important.



M1= 0.535 M2= 0.504
P1= -179.898 P2= 139.381
315.001MHz 315.012MHz

Fig. 7: R851 in 1-port configuration: GD[S33]

In the Colpitz SAWR oscillator we use the SAWR in one-port configuration. Therefore we are interested in the location of the GD[S33] maximum. We have to adjust the oscillating frequency in this way, working closely to the maximum GD[S33] point.
Remember – In Circuit Q of the SAWR is proportional to the GD[S33]!!!!
The frequency offset between GD[S33] maximum and Re[Y11] maximum is about 12kHz for the R851.
The reason for this frequency offset is the effect of the shunt capacity "C0 // Cgnd", parallel to the SAW resonator core (Lm, Rm, Cm).

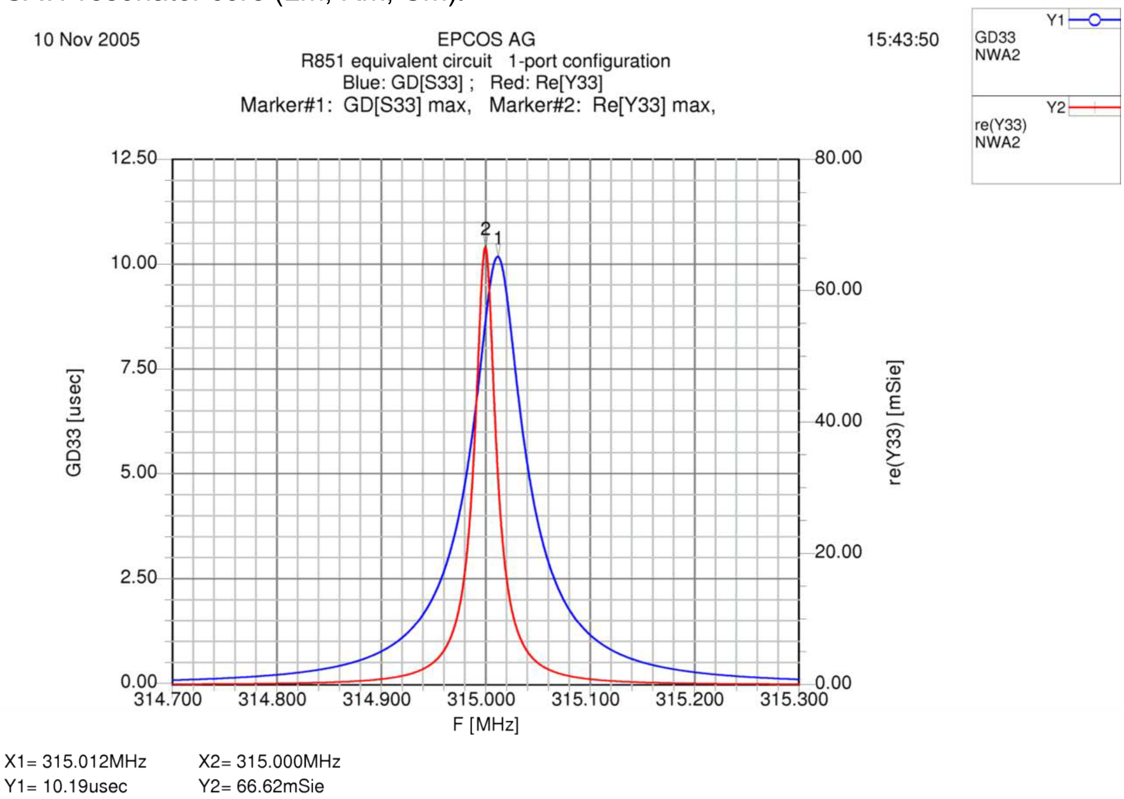


Fig. 8: R851 in 1-port configuration: GD[S33], Re[Y11]

Effect on oscillator circuit adjustment:
Best frequency stability of the SAWR Oscillator can be obtained by working at maximum group-delay (best Q-factors) of the SAWR. This results in a slight high tuning of the SAWR Oscillator of about 12kHz (R851).
Tuning the oscillator exact at his resonance frequency (Re[Y11] maximum), In Circuit (loaded Q) is about 10% less, which does not create a problem. Assuming component tolerances of the oscillator active part, which drops down the Oscillation frequency further more, loaded Q-factor is declined further more.
For the R851 we can fix a certain bandwidth where the GD[S33] comes down to 0.5.
The 0.5*GD[S33] bandwidth is about 60kHz.
We recommend to adjust the SAWR oscillator between the maxima points of GD[S33] and Re[Y11] to provide best frequency stability an minimum sensitivity in point of component tolerances.

Taking the oscillator´s component tolerances (NON-SAW tolerances) into account, the well tuned oscillation frequency (tuned close to maximum loaded Q-factor of the SAWR) can differ over mass-production. To avoid this we recommend to use tight tolerance components for C_{E-GND} (±2%), C_{C-E} (±0.1pF), $C_{load\ transformed}$ (±0.1pF) and for $L_{Collector}$ (±2%).

On the other hand the SAWR oscillator´s start up time is in a maximum, working at maximum loaded Q-factor / maximum of GD[S33]. The energy stored in the SAW resonator is maximal. During start up phase, this electrical energy has to be converted into acoustic energy stored inside the SAWR´s cavity. Working at best loaded Q-factor, more acoustic energy has to be collected inside the acoustic cavity of the SAWR. The start up time takes longer.
Tuning an SAWR oscillator significant low (e.g. -50kHz off from GD[S33]), loaded Q-factor becomes really small and start up time is speed up. Frequency stability and temperature stability becomes worse. To improve the start up time of the oscillator by adjusting the frequency more low is not the right way, because frequency stability is gone.

Accelerating the SAWR Oscillator’s start up time and minimising the ghosting.
The SAWR oscillator start up is a very dynamic process. It is difficult to get a detailed understanding. Therefore we crated following scenario:

Switching on the power supply
- Small signal DC bias points in the oscillator circuit are adjusted.
- There is no energy stored in the SAWR and in the LC tank yet.
- The serial electrical resonance circuit (Lm,Rm,Cm) is established yet, but there is no energy stored in the electrical resonance circuit.

Staring the free wheeling LC oscilltion
- Oscillation grows up slowly at the free wheeling start up oscillator frequency. (fixed by the LC tank circuit and the certain grounding conditions of the transisor´s base). Up to now the transistor´s base is mainly grounded by the shunt capacitor C0. The current into the SAWR is very week. C0 is the master. The transistor works in his linear range.
  The free wheeling start up oscillator frequency is about 20MHz…60MHz higher than the free wheeling oscillator frequency in steady state mode. Spectrum purity is poor. The LC controlled frequency is changing during the early start up process and provides signal energy at the SAWR´s resonance frequency as well because of wideband noise. Wideband noise energy and the LC oscillation noise at the SAWR´s resonance frequency is stored in the SAW resonator and creates a standing electrical wave inside the SAWR´s cavity. The free wheeling start up oscillation frequency is important to generate continuous noise energy during start up phase to pump the SAW resonator.
  Comment: Gain of the active oscillator part, depends in the base grounding conditions. Providing a more worse grounding, the oscillator gain is less. Improving the grounding, oscillator´s loop gain grows up. For a Colpitz oscillator with grounded base, base grounding is important from the very first. In case of the SAW Oscillator the initial grounding is done by the SAWR´s shunt capacity. This shunt capacity is very important here. Without C0 the SAW oscillator will not start.
- More and more energy is stored in the SAWR, current into the SAWR increases. The free wheeling start up oscillation frequency moves into the direction of the SAW resonator´s resonance frequency. Signal spectral purity is improved, sideband noise is suppressed.

Reaching the steady state mode of the SAWR oscillator
- Finally stored energy in the SAWR is in a maximum, the SAWR is the master and the Oscillator becomes working in steady state mode. The transistor works non linear, in compression range. The loop gain is reduced to 1.

Comparing the free wheeling start up oscillator frequency with the free wheeling oscillator frequency in steady state mode (replacing the SAWR by about 15 Ohm // 3.3pF) we find a difference. In the early start up process the transistor´s bases is grounded by the shunt capacitor C0 only, in steady state mode, exactly at SAWR´s resonance frequency, transistor´s bases is grounded by 15 Ω // 3.3pF (Rm // C0). Phase condition of transistor´s grounding during start up phase and in steady state mode is different. This results into a higher free wheeling start up oscillator frequency. The free wheeling start up oscillator frequency normally rests only for a very short time, the power level is very week. Sometimes the free wheeling start up oscillator frequency lives much longer, provides a high power level before the SAWR controls the oscillation frequency fully. We call this effect “Ghosting”. Ghosting can be checked at the spectrum-analyser by modulating the SAWR oscillator ON / OFF.

Ghosting appears in a SAWR based Colpitz oscillator with grounded base in case of:

- Wide LC tank circuit (relative high collector inductance, small $C_{C\text{-}E}$)
- Strong feedback , low $C_{E\text{-}GND}$ / $C_{C\text{-}E}$ relation, high loop gain
- No Collector load, especially for the Colpitz version using the emitter for output
- Increasing Vcc, ghosting is forced.

Countermeasures:

- Tighten the LC tank by increasing $C_{C\text{-}E}$ and reducing $L_{Collector}$. $L_{Collector}$ should be in the range of j 50...60 Ω for a lumped inductor. A higher $C_{C\text{-}E}$ helps as well to attenuate the harmonics of the oscillator signal.
- Increase $C_{E\text{-}GND}$, but this has an effect on output power especially for the emitter OUT version. $C_{E\text{-}GND}$ should provide about -j 25 Ω.
  A more slow transistor with a moderate F_t provides less gain (less steepness). The loop gain will not exceed. We use for SAWR based Colpitz oscillators the BFS17w or the BFR92w. BFS17w is often cheaper, but the oscillator´s start up time takes longer.
- Comparing the collector loading between a Colpitz structure using the collector output with the emitter output version, we have an additional collector loading using the collector output.
  Assuming the final load is 50 Ω, a serial matching capacitor between collector and 50 Ω load is required. For a 315MHz oscillator this capacitor is in the rage of 3p9F…5p6F. This capacitor should be chosen for best power matching, but has a significant influence to the correct oscillator frequency tuning.
  Transforming the 50 Ω load via the serial capacitor to the collector, the collector is loaded by about 400 Ω // 3p9F (315MHz oscillator, BFR92w). The entire tank circuit (consisting of $C_{E\text{-}GND}$ / $C_{C\text{-}E}$, $L_{Collector}$, $C_{C\text{-}transistor}$, $C_{load\ transformed}$) is used only partly for the loop feedback. The entire LC resonance current is spited into the segment $C_{E\text{-}GND}$ / $C_{C\text{-}E}$, $C_{C\text{-}transistor}$ and the segment $C_{load\ transformed}$ whereas this current is not used in the feedback loop. The feedback loop current is reduced.
  => especially for the oscillator, working with emitter output, it is recommended to add a additional low tolerance capacitor (+-0.1pF) in parallel to the $L_{Collector}$ to reduce the feedback current. Sometimes a reduction of the $L_{Collector}$ Q-factor by adding in parallel a resistor with 1k Ω helps to avoid Ghosting.

The reason for Ghosting is the frequency offset between the free wheeling start up oscillator frequency with the free wheeling oscillator frequency in steady state mode. First we ground the transistor´s base via 3p3F, because the SAWR shows more high impedance characteristic during early start up phase. Secondly in steady state mode the transistor´s base is grounded by 15 Ω // 3.3pF (Rm // C0). To move the free wheeling start up oscillator frequency closer to the wheeling oscillator frequency in steady state mode, we have to add a additional resistor in parallel to C0. Transistor´s base is grounded now by 3p3F // Rx. Phase condition in the loop is changed and the free wheeling start up oscillator frequency moves down. Evaluated on our experiments (315MHz SAWR based Oscillator, emitter out) we used about 180 Ω for Rx. A higher values would be more recommended, but keeps the positive effect low.

<u>We face two benefits:</u>

- A lower free wheeling start up oscillator frequency fits better to the final free wheeling oscillator frequency in steady state mode. If ghosting still appears, ghosting rests not so long and at a lower power level.
- Wideband noise power generated by the free wheeling start up oscillator frequency provides more energy at the SAWR´s resonance frequency (because both frequencies are closer now). More energy at SAWR´s resonance frequency during start up phase speeds the generation of the standing wave in the SAWR´s cavity. The SAWR becomes the master faster in the oscillator loop.

<u>Attached a SAWR based Colpitz designed for 315MHz</u>

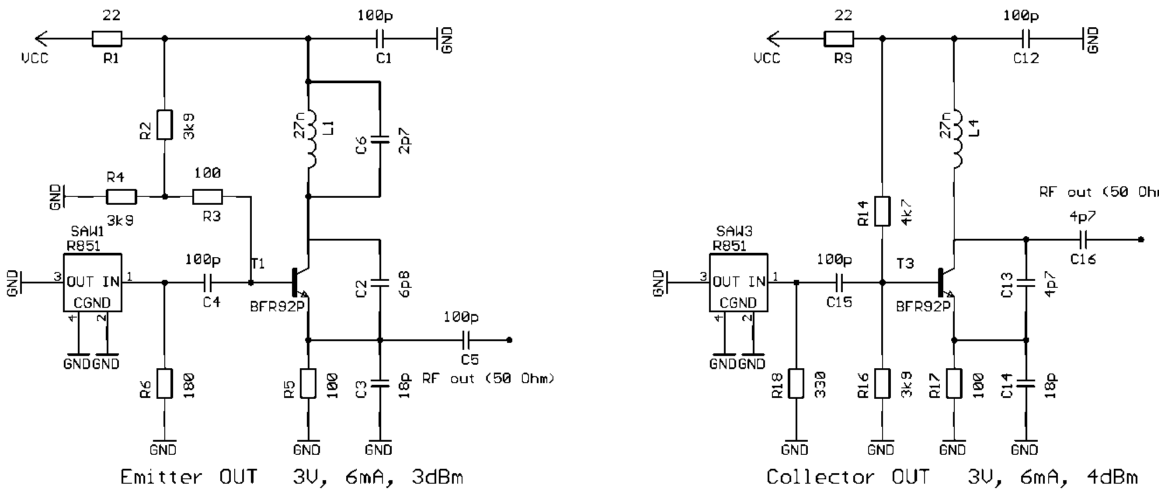


Fig. 9: SAWR based Colpitz oscillator, providing the emitter or the collector for output

The advantage of the <u>emitter output</u> version is significant less load sensitivity. Load pulling (change of load vs. frequency) is much better. Output impedance is low (about 20…50 Ω).
The antenna / buffer amplifier has to fit to this impedance environment.
This approach provides less sensitivity in point of component tolerances.
Harmonics are quite low.
The drawback is a slightly lower output power and a lower efficiency.

With the <u>collector output</u> solution, output power can be maximised. A a NOT-constant load changes the free wheeling oscillation frequency of the SAWR oscillator significant. The external load is transformed to the collector and influence the LC tank.
The load can be an antenna or the input of a buffer stage. Both structures are presenting a variable input impedance.

The <u>collector output</u> structure is widely used for the RC key-fob (Remote control entry). $L_{Collector}$ is substituted by a loop antenna. The loop antenna is part of the LC tank circuit and affects the entire SAWR oscillator. There is no external load.

Appendix

Calculating the drift of the center frequency of a SAW resonator in a certain operating temperature range

These days EPCOS SAW resonators are available with process tolerances / initial tolerance of ± 50kHz, ± 75kHz and ± 100kHz. Calculating the over all frequency deviation of a SAW based oscillator initial tolerance distribution and the temperature performance of all components is required.
Attached a short description to calculate the frequency deviation over temperature for a SAW resonator centred at **315.02MHz** (R851)..

Frequency deviation over temperature for a SAW Resonator on quartz substrate material follows a negative parabolic shape.

$$fc(T_A) = fc(T0)(1 + TC_f (T_A - T_0)^2)$$

$f_C(T_A)$ frequency at a certain ambient temperature
$f_C(T0)$ frequency at the turnover point (mainly close to the SAWR´s center frequency)
TC_f temperature coefficient. This value is negative!!!
T_A ambient temperature at which the frequency has to be known
T_0 turnoverpoint.

Characteristics

Reference temperature: T_A = 25 °C
Terminating source impedance: Z_S = 50 Ω
Terminating load impedance: Z_L = 50 Ω

		min.	typ.	max.	
Center frequency 1)	f_c	314,97	315,02	315,07	MHz
Minimum insertion attenuation	α_{min}	—	1,3	1,6	dB
Unloaded quality factor	Q_U	8300	13200	—	
Ageing of f_c		—	—	–10/+50	ppm
Equivalent circuit elements					
Motional capacitance	C_1	—	2,47	—	fF
Motional inductance	L_1	—	103,34	—	µH
Motional resistance	R_1	—	15	20	Ω
Parallel capacitance 2)	C_0	—	3,2	—	pF
Temperature coefficient of frequency 3)	TC_f	—	–0,032	—	ppm/K²
Turnover temperature	T_0	25	35	45	°C

1) Center frequency is defined as maximum of the real part of the admittance

2) If used in two port configuration (pin 1-input, pin 3-output) C_0 is reduced by approx. 0,3 pF.

3) Temperature dependence of f_c: $f_c(T_A) = f_c(T_0)(1 + TC_f(T_A - T_0)^2)$

Fig. 10: Datasheet extraction of R851

Maximum resonance frequency of the SAWR is achieved at his turn-over-temperature (TOT). Below and above the TOT, resonance frequency of the SAWR always goes down. The resonance frequency of the SAWR follows a negative parabola (ppm/$\mathbf{K}^2$).
Starting at the turn over point (maximum of the negative parabola) the frequency always goes downwards anyway the direction to go. Moving the SAWR´s resonance frequency over temperature, the maximum Q-factor moves accordingly.
Due to this fact the nominal centre frequency of the R851 has been moved 20kHz above 315MHz. The entire frequency drift over temperature goes into “down” direction, is spited now into a drift segment of 50% going down and 50% going up relative to 315MHz. The SAWR´s frequency drift becomes more symmetrical over temperature. This helps in the receiver to use the IF filter bandwidth more efficiently.

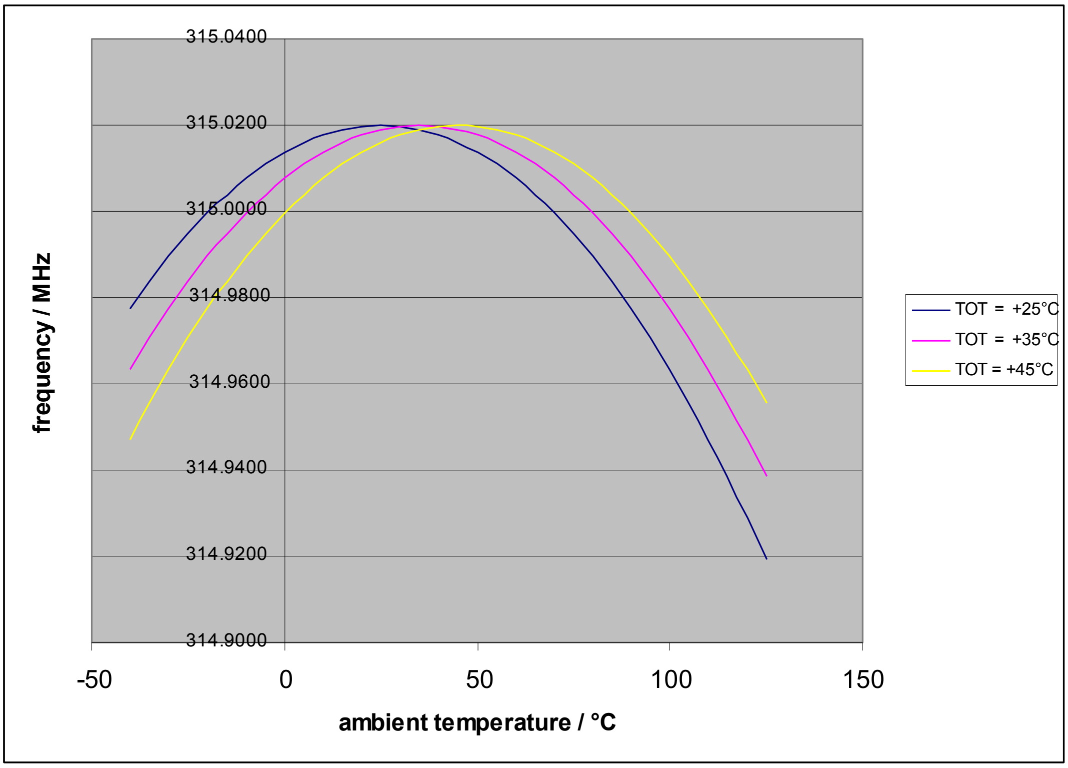


Fig. 11: Frequency deviation over temperature at different TOTs

Depending on the location of the TOT, the frequency drift for a certain temperature range is higher either above or below the TOT. To avoid this it is useful to choose the TOT in the middle of the specified operating temperature range.

For a Tire Pressure Monitoring Systems (TPMS) an operating temperature range of -40°C…+125°C is required.
The recommended TOT should be placed in the centre temperature of the required operating temperature range. 42.5°C would fit for TPMS requirements perfectly. The TOT can be pushed into the right direction, by the SAW manufacturer using an dedicated crystal quartz cut for the SAWR substrate. The optimum TOT for the SAWR can not be obtained exactly which results in the minimum and maximum specification for TOT in data sheet. For high temperature applications we designed the R851 with a typical TOT @ 35°C. This Resonator is not far away from the optimum TOT for TPMS applications.

Calculation example:

- Operating temperature range: **-40 …..+125°C**
- temperature coefficient of the SAWR: **-0.032ppm/K²**

Using the following equation:

$$fc(T_A) = fc(T0)(1 + TC_f(T_A - T_0)^2)$$

$f_C(T_A)$ frequency at a certain ambient temperature
$f_C(T0)$ frequency at the turnover point (mainly close to the SAWR´s center frequency)
TC_f temperature coefficient. This value is negative!!!
T_A ambient temperature at which the frequency has to be known
T_0 turnoverpoint.

The typical turn-over-point for the R851 is 35°C, centre frequency is 315.02 MHz.
By the way, for calculating the worst case frequency deviation over temperature, the minimum and the maximum value for the TOT has been take into account
Frequency deviation for a temperature range of -40°C and +125°C is calculated:

f_C(-40) = 315.02e⁶*(1+(-0.032e⁻⁶)*(-40-35)²) = **314.963MHz**
f_C(+125) = 315.02e6*(1+(-0.032e⁻⁶)*(125-35)²) = **314.938MHz**

Relative to **315.00MHz!!** this is a frequency drift of:
-37kHz @ -40°C
-62kHz @ +125°C
Frequency at TOT is about 315.02MHz. Freq. deviation: -37kHz / -62kHz…+20kHz

If the centre frequency of the SAW would be exactly **315.00MHz** (no pre-compensation implemented) the frequency drift relative to 315.00MHz would be:
-56.7kHz @--40°C
-81.6kHz @ +125°C
Frequency at TOT is about 315.00MHz. Freq. deviation: -57kHz / -82kHz...+0kHz

The pre-compensation make the entire frequency deviation over temperature more symmetrical referenced to a dedicated frequency (here 315.00MHz)

But this has to be done carefully in order to stay below the upper test limits of the final transmitter measurement at ambient temperature in the customer´s back end of production. Working with a high pre-compensation frequency offset the upper frequency limit of the entire SAWR oscillator (including his component tolerances) can be exceeded.