Application Note
SAW-Components

Comparison between negative impedance oscillator (Colpitz oscillator) and feedback oscillator (Pierce structure)
App.: Note #13

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Comparison between negative impedance oscillator (Colpitz oscillator) and feedback oscillator (Pierce structure)

Different approaches are possible for a SAW resonator (SAWR) stabilised oscillator. TX frequency, modulation technique and economy determine the basic structure.

Negative impedance oscillator (Colpitz oscillator)

General principle

Up to 500MHz usually the negative impedance oscillator (Colpitz structure) is used. The Colpitz oscillator divides into an active and a passive one-port.

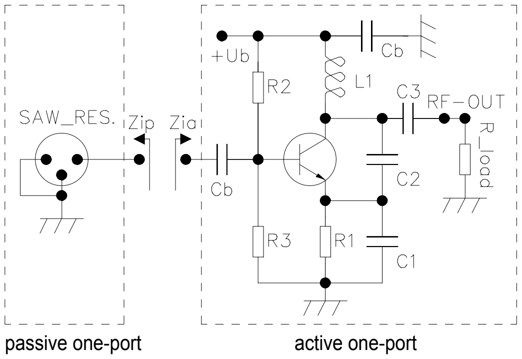


Fig.1: Colpitz oscillator, divided into passive and active network

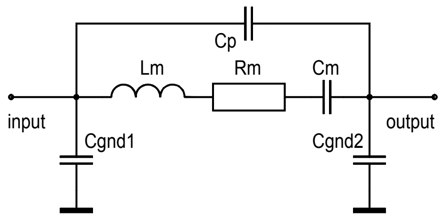


Fig.2a: Equivalent circuit of a one-port SAWR

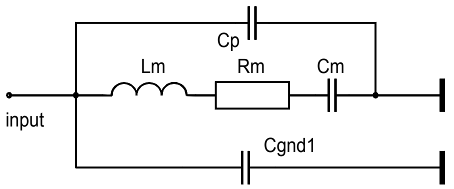


Fig.2b: one-port SAWR, used in a Colpitz oscillator

Real part of input impedance at the active one-port = Re{Zia}
Imaginary part of input impedance at the active one-port = Im{Zia}
Real part of input impedance at the passive one-port = Re{Zip}
Imaginary part of input impedance at the passive one-port = Im{Zip}

The passive one-port is the SAWR, whereas the active one-port consists of a transistor, the load and a feedback network. The real part of the input impedance (Re{Zia}) is negative around the SAWR resonance frequency. The imaginary part of the input impedance (Im{Zia}) should be close to zero.
For starting oscillation, the following equations are important:

- Re{Zia} + Re{Zip} < 0
- Im{Zia} + Im{Zip} = 0

The sum of Re{Zia}+Re{Zip} must be negative, to compensate the loss of the passive one-port and for raising the oscillator signal from the thermal noise level to a steady state signal.

Moreover, the oscillation will only start, if Im{Zia} + Im{Zip} is zero at SAWR resonance frequency. Having a high offset at Im{Zia}, the SAWR must compensate this offset by his Im{Zip}. Best oscillation stability (best loaded Q-factor) is achieved by tuning the oscillation to the serial resonance frequency of the SAWR. Here Re{Zip} is minimised and Im{Zip} is zero. In this case there is no offset for Im{Zia}.

Feedback in the active one-port consists of a capacitive taped parallel circuit (tank circuit). The capacitive part of this tank circuit is $C_{C\text{-}E}$, $C_{E\text{-}GND}$, and the transistor's output capacitance. The inductive part is the collector inductivity, which is a concentrated coil or a printed loop antenna. The taped tank circuit, in combination with the transistor, creates the negative input impedance at the transistor's base. Grounding the transistor's base via a low impedance, oscillation will start at the resonance frequency of the tank circuit. This is why this oscillator structure is called Colpitz oscillator with grounded base (common base).

In a SAWR stabilised oscillator oscillation starts at the LC circuit and increase in amplitude. The characteristic of the SAWR is undefined during the transient time (oscillator's start up time) of the oscillator. More and more RF energy is fed into the SAWR and stored there. The SAWR dominates more and more and increase stability of the oscillation frequency. Large signal effects reduce the gain of the active one-port to 1. Now steady state mode is reached.

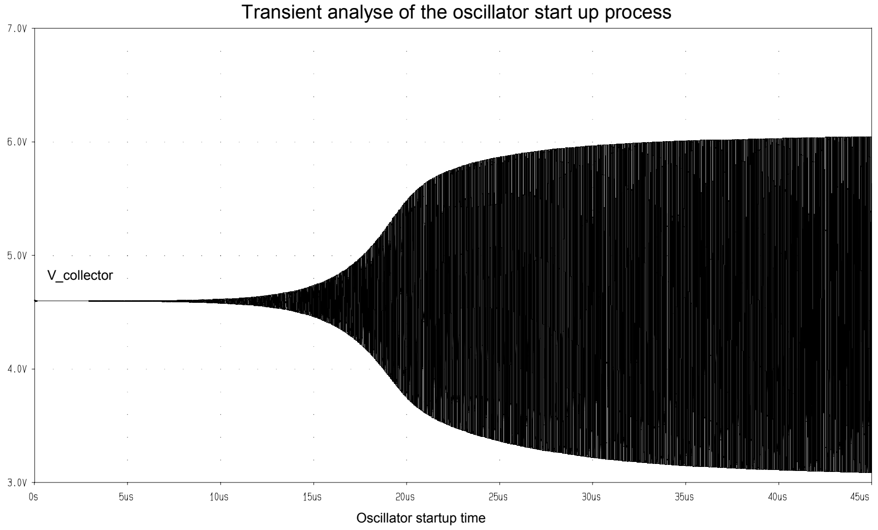


Fig.3: Start-up process of a Colpitz oscillator (@434MHz), monitored at the collector voltage

An oscillator's start up time is determined mostly by the loaded Q-factor of the SAWR and moreover by the total gain in the active one port. With increasing loaded Q-factor, the start up time will increase. A high loaded Q-factor grants a good frequency stability. Moving the oscillation frequency away from the best loaded Q-factor (@ serial resonance frequency of the SAWR), will decrease frequency stability.
Adjusting the LC oscillation close to the desired SAWR serial resonance frequency, frequency stability and start-up time is maximised.

Starting the development of a Colpitz oscillator

For calculating the component values of the taped tank circuit, the following equation can be used:

$$Fp = \frac{1}{2 * Pi * \sqrt{L1 * \frac{C1 * C2}{C1 + C2}}}$$

In this equation the transistor's output capacitance and the load effect are neglected. In reality the free running LC oscillation will be lower than calculated.
Using the oscillator in a LO configuration with a external load, L1 is normally located around j60 Ohm. For a transmitter with a loop antenna, L1 often is higher (approx. j90...j110 Ohm).
The feedback ratio $C_{E\text{-}GND}$ / $C_{C\text{-}E}$ depends on the gain of the transistor. Using a high speed transistor, the ratio must be high to keep feedback small.
Using a transistor with a transit frequency (Ft) of about 3...5 times the SAWR resonance frequency, feedback ratio should be 3...6.
To keep the harmonics low, a high speed transistor is not recommended.

The coupling capacitor between the SAWR and the active one-port is not critical. A value between 47pF and 220pF is ok.

In order to determine the component values on the PCB, the following procedure can be used:
Before starting to optimise the PCB, the load (i.e. mixer, antenna active) must be connected to the oscillator to get the correct loading effect. The SAWR is replaced by a 22 Ohm resistor and a parallel capacitor of about 2p7F. This RC combination simulates a SAWR at serial resonance frequency in a wide frequency range.
The oscillator starts up oscillation at LC circuit frequency. The oscillator frequency can be trimmed by C1!, C2, C3 (and L1). The free-running LC oscillation frequency should be close to the desired SAWR frequency (-10MHz...+20MHz). Replacing R and C by SAWR, the frequency is stabilised on the desired value of the SAWR.

Having a strong gain in the oscillator circuit and the LC oscillation is not at the right frequency range (tuned to a high value), a kind of spurious oscillation (ghost oscillation) can sometimes occur during the start up time of the oscillator. This ghost oscillation can be displayed on a spectrum analyser, when the oscillator is OOK modulated (On-Off-Keying). The oscillator starts first at the LC tank resonance, which is 30MHz...80MHz above the SAWR frequency. After the transient time of the SAWR, (max 100usec, typical 50usec) the oscillation frequency is caught and stabilised by the SAWR. The ghost oscillation stops.
To avoid this ghost frequency, the ratio $C_{E\text{-}GND}$ / $C_{C\text{-}E}$ should be increased. This measure reduces feedback. Usually, an increase of $C_{E\text{-}GND}$ is effective. Often a resistor of about 22 Ohm in serial to $C_{C\text{-}E}$ stops the ghost signal, too.
Furthermore a exact tuning of the oscillator's natural oscillation frequency to the desired SAWR frequency is necessary.

Features of a Colpitz oscillator

The structure of the Colpitz oscillator is very simple. The design is easy to do.
OOK is the best modulation technique for low data rates.
The current consumption is low and can be further reduced by using OOK modulation.

The limit of the SAWR stabilised Colpitz oscillator is 500...600MHz. The equivalent circuit of a SAWR is a serial LRC resonance circuit with a extremely high Q-factor and a parallel capacitance C_p (refer Fig.2a,b).

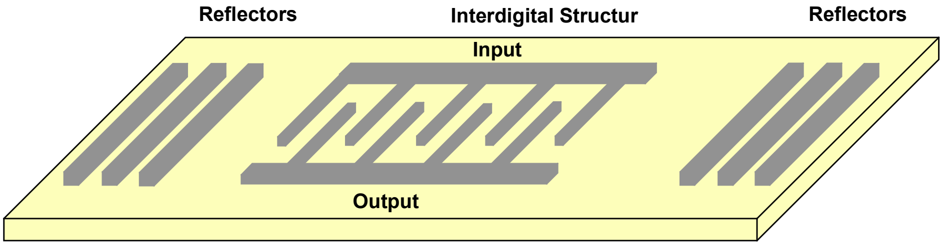


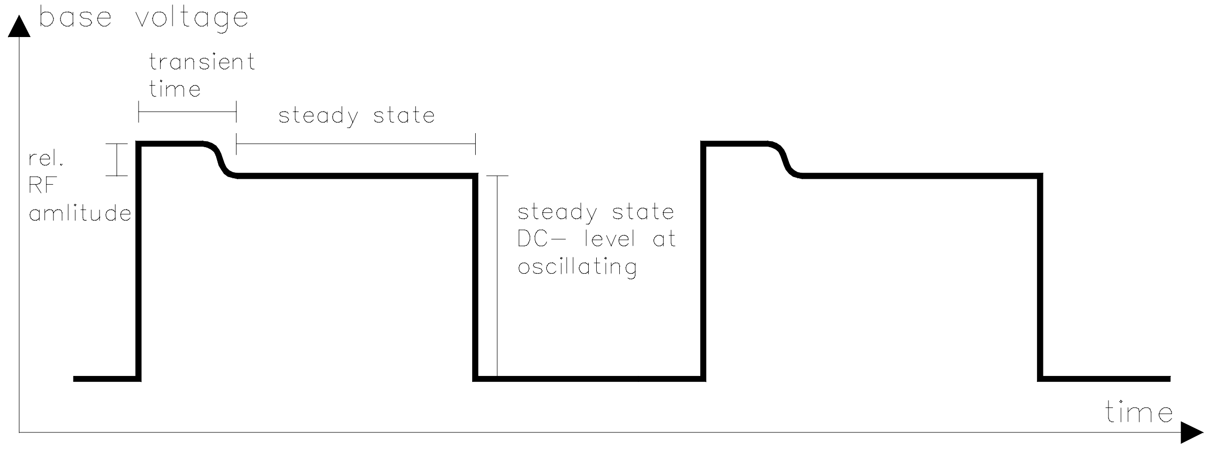
Fig.4: Simplified internal structure of a one-port SAWR

C_p is the coupling capacitance between the SAWR interdigital fingers and the capacitance of the input and output pins to ground. C_p provides a parallel path to the LRC resonator. Increasing the SAWR frequency (above 500MHz) the impedance of the shunt path is reduced. Dominance of the SAWR is limited to a narrow frequency band at serial resonance frequency. The ultimate rejection is more and more determined by the shunt capacitor C_p . This can promote an oscillation on any other frequency besides the SAWR resonance frequency
A further problem of a very high frequency (868MHz) Colpitz oscillator is the collector inductivity. The value of the coil is as low as 8...12nH. The size of a printed loop antenna with such a low inductivity is very small, which is unfavourable, because radiated power depends on the area of the loop antenna.
For high frequency oscillators (< 500...600MHz) more benefits can be achieved with a Pierce oscillator and a 2-port SAWR.

A example for a Colpitz based transmitter with a integrated loop antenna (@434MHz) is given in application note ”App#1”.

Measurement of the oscillator's transient time (start up time) by measuring the transistor's bias voltage in modulation mode.

The RF amplitude at the transistor's base-pin changes the DC level a little bit. A higher RF amplitude causes a stronger deforming. The DC level at the transistor’s base in oscillation- and non-oscillation mode depends on the RF swing at the transistor’s base, on the value of the resistor from base to the modulation IC and on the emitter resistor.
Growing up of the RF voltage during the oscillation start up, the base current changes. Using an serial resistor (22K...68K) from the data source to the transistor’s base, the voltage drop at this resistors increases. The result is a lower base voltage. Using a resistive divider (mostly lower in impedance) to generate the base voltage, the base voltage is more fixed and the effect is not so strong.
When the oscillator is modulated at his base, the oscillation starts up every rising base voltage edge. For monitoring the voltage shape at the transistor's base, a oscilloscope is connected to the transistor's base by a 22K...33K resistor. The resistor isolates the probe capacity from the transistor's base. Without resistor the oscillation sometimes stops by capacitive loading effects. On the scope the high state is separated in two sections. A short higher area and the large lower area. In the high area the RF voltage swing at the transistor's base is very small. The oscillator is starting oscillation. At the lower area the oscillator is in steady state mode. The RF voltage is in a fixed maximum and drop down the base voltage a little bit.
The transient time is the time step of the high level period. Working on high Q- area (close to the SAWR´s serial resonance frequency), the transient time is often long. If the start up time is very short (< 5 usec) the oscillator works out of his stabilisation range. The frequency stability is mostly poor.



Base voltage of the transistor in modulation and oscillation mode

A similar measurement can be done at the emitter with less loading effect.
At the transistor’s base this effect is more significant.
General remarks: If a complete base voltage divider (2*resistors) is used, base voltage is nearly locked. This effect is very small, or can not be monitored.

This technique can be used for a Colpitz and a Pierce oscillator in the same way.

Feedback oscillator (Pierce oscillator)

General structure

For high frequency oscillator designs at 500MHz....1000MHz, another oscillator approach is more convenient. The structure is a feedback oscillator, often called Pierce oscillator.
The advantage of this approach is a design with less parasitic effects.
The feedback oscillator is an unconditional stable amplifier with a signal feedback from the output to the input. The feedback consists of two ”PI” matching networks and a two-port SAW resonator. For this oscillator a SAWR with 180° phase shift between input and output is used.
The load (often 50 Ohm) is connected to the collector via a small capacitor. This capacitor transforms the high impedance level of the collector to the desired load impedance.

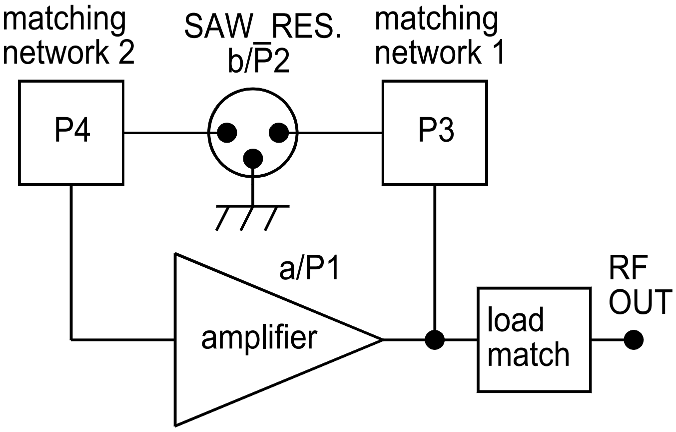


Fig.5: Pierce oscillator working with a SAWR

For starting oscillation the two Barkhausen conditions must be fulfilled.

- amplitude: $G = a + b > 1$
- phase: $Ptot = P1 + P2 + P3 + P4 = n * 360°$
  $n=0,1,2,...$

For a high gain amplifier it is easy to meet the amplitude condition, but if the phase condition is not fulfilled, no oscillation will occur or the oscillation frequency will be not at the serial resonance frequency of the SAWR. This frequency deviation causes an additional insertion loss of the SAWR. A high deviation results in a oscillator loop gain <1. The oscillation will not grow up from noise level.

Insertion loss of a two-port SAWR at resonance frequency, is determined on load and source impedance. Increasing the load and source impedance
for the SAWR, insertion loss will reduce.
On the other hand the loaded Q-factor will be reduced too.
A high impedance level at the SAWR´s input and output will help the designer to realise a high enough gain in the loop, but the frequency stability will be reduced, because of the lower loaded Q-factor.

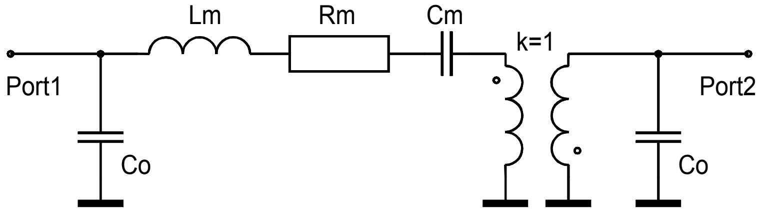


Fig.6: Equivalent circuit of a 2-port SAWR with 180° degree phase shift

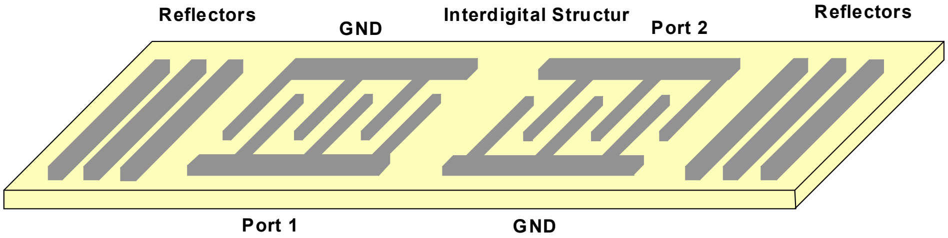


Fig.7: Simplified internal structure of a two-port SAWR

$$Ql = \frac{Qu * Rm}{Rm + Rs + Rl}$$

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

Ql = loaded Q-factor
Qu = unloaded Q-factor
IL = insertion loss of the SAWR in [dB]
Rl = load impedance of the SAWR (real value)
Rs = source impedance of the SAWR (real value)
Rm = motional resistance of the SAWR
Cm = motional capacitor of the SAWR
Lm = motional inductivity of the SAWR
Rm, Cm, Lm are characterised in the equivalent circuit of the SAWR
3dB bandwidth (BW) of the SAWR = fosc/Ql

For the matching networks a ”PI” structure with two capacitors and one inductor is being used ([Cp1,Ls1,Cp2],[Cp2,Ls2,Cp4]). The two internal grounding capacitors (Co) of the SAWR are a part of Cp1 and Cp3. Depending on oscillation-frequency and on PCB layout, sometimes the capacitors of the ”Pi” matching-network can be removed.

The matching network between the collector and the transistor transforms the high collector impedance to a lower source impedance for the SAWR. The second matching network transforms the base impedance to the desired SAWR load impedance. Additionally the two matching networks create a certain phase shift to fulfil the phase condition in the oscillator loop.

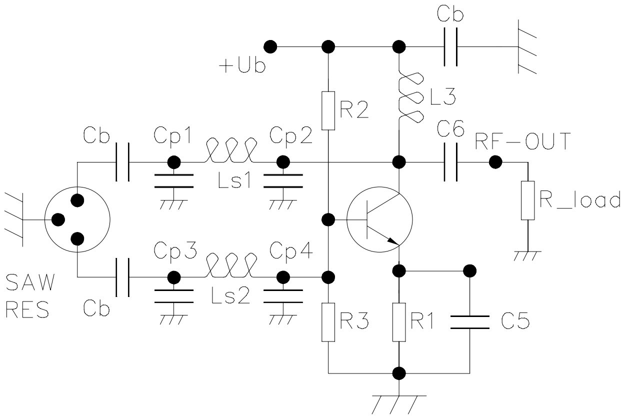


Fig.8: Pierce oscillator in his general form

Calculating the circuit for a certain source and load impedance analytically is hard, because of the interaction between the different oscillator parts.
It is easier to start the development within a 50 Ohm system. The design can be done with a 50 Ohm gain block, a power divider for power output and a phase shifter in 50 Ohm technique. The disadvantage here is the high current consumption by using the 50 Ohm gain blocks. For a low current solution a discrete design, working at a higher impedance level is more recommended.
For starting this design the general calculation can be done with a RF simulator. Fine tuning of the oscillator frequency should be done later on the oscillator board.

Simulation technique for starting the Pierce oscillator design

The S-parameter of popular RF transistors are available (i.e. @ the WWW) and the equivalent circuit of the SAWR is specified on the data sheet. It is recommended to use the equivalent circuits for the other components, too (parallel capacitor of the inductivities) to be more realistic in simulation.
The closed oscillator loop is described in the simulation tool and at collector's node S11 and Z1 are measured. It is important to connect the desired load to the collector via a small capacitor.

The oscillation will start, if both conditions are fulfilled

- Mag [S11] >1 at the desired oscillation frequency
- Ang [S11] is close to 0°degree at the desired oscillation frequency

S11 can be monitored in the extended Smith chart. S11 at the desired SAWR is placed in the extended Smith chart part (S11>1) and close to the centre line of the Smith chart.
The phase of S11 is > 0° below, and < 0° above oscillation frequency. Tune the component values to fulfil these conditions.

Benefits of a feedback Pierce oscillator

The advantage of a feedback oscillator with a 2-port SAWR is a design with less parasitics. There is no parallel capacitance between input and output. The capacitances to GND are added to the ”PI” matching network. The SAWR is used like an ideal LRC serial resonator. The frequency stability can be achieved at high frequency, too. A spurious oscillation at another frequency will not occur, because of the good ultimate rejection (refer Fig.6).
For a feedback oscillator in a transmitter with an integrated loop antenna, a special feedback structure was developed. The feedback consists of a loop antenna and the SAWR. Additional capacitors ($C_{C\text{-}E}$, $C_{E\text{-}GND}$) are added. The current from collector passes the loop antenna and then the SAWR. The used loop antenna is much larger then the loop antenna in a Colpitz oscillator (@868MHz). The radiated power depends on the size of the loop antenna.

For application example, a classic Pierce oscillator (@915MHz) is described in application note ”SAW_OSZ6”. An example for a modified Pierce oscillator (@868MHz) with an integrated loop antenna for transmitter use is given in application note ”SAW_OSZ4”.

Remarks to the PCB layout of all oscillator structures

It is important to create a good RF PCB layout for a stable design. A double side PCB with closed grounding plane at the bottom side is necessary. Do not connect grounding nodes by thin PCB tracks. Place enough through holes (via holes) at the grounding nodes of the devices to achieve a low impedance path to the grounding layer. Keep all PCB tracks short. The whole RF design should be compact. Keep the loop antenna area free of grounding area. Layout recommendations can be found in our other application notes.

General hints for PDF file printing: Best result using a Post Script printer in PS mode.

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