Reproducible Low Noise Oscillators

Summary

In the last decades much has been published about the noise performance of oscillators. Also descriptions of measuring methods passed in revue. The articles in question approached just parts of the problem so that up till now there was no recipe to configure low noise oscillators. In this article a separation between essentials and side-issues is made: Q-degradation, AM to FM conversion and microfonism are main issues. An 'extra agc' with a small schottky diode, a small coupling capacitor and matched leakage resistor solves the main problems. It kills at least two birds with one stone.

As base serves the well known over 60 years old Clapp oscillator with a JFET as active element. The two amplitude stabilisation mechanisms are treated and the solution is given to avoid damping of the resonator and to prevent AM to FM conversion with the aid of an 'extra agc' which makes the circuit reproducible as an added advantage!

With this LC-oscillator the mechanical tuning is rejected, and problems with varicaps (VCO's) and magnetic materials are treated.

Finally the Xtal oscillator (clock oscillator) passes in review in relation to the 'extra agc'.

Eventually the recipe is offered how to configure a low noise oscillator without the need of complex measurements.

Preface

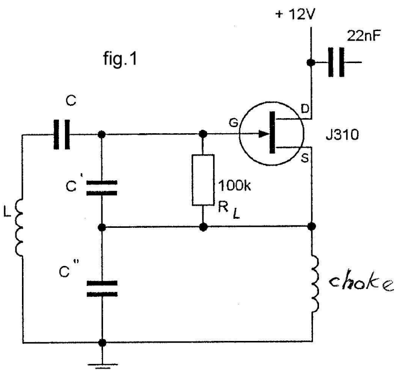
Much has been published about the noise performance of oscillators the last decades. Many theoretical approaches with extended mathematical proofs as well as circuits of skilful electronic engineers passed in revue.

The measurement of the noise performance of an oscillator is another problem. All attempts building a low noise oscillator were associated with such measurements. Apparently there was no simple recipe, not to mention a formula for a *reproducible* circuit that offers an outstanding performance. Up till now.....

I expect that the reader knows that the noise performance of an oscillator is strongly related to the quality factor (Q) of the resonator, the handled power by this resonator, etc.

I even expect familiarity with the Clapp oscillator (fig. 1) which became popular as a tube-configuration in the forties of the previous century. This circuit is the basis of *the reproducible low noise oscillator circuit* presented here. It suites the frequency range of hundred kilohertz up to hundred megahertz.

Dimensioning the Clapp oscillator



In fig.1 the circuit of the Clapp oscillator is presented. The FET is a JFET as the J310 with I_{gss} > 20 mA. After many examinations MOS FETs or bipolar transistors have been proved to be less suitable.

C ...(pF) ≈ 500/f_0, if f_0 is the resonance frequency in MHz.

C' = C'' ≈ 4.C

L ...(µH) from $40.f_0^2.L.C_0=1$. With C_0 = 2C/3 in this case.

R_l ≈ 100 kΩ or larger.

'choke'...(µH) $\approx 200/f_0$ if f_0 is in MHz.

This oscillator operates well but is not a real low noise oscillator.

Amplitude Stabilisation

In an oscillator are two mechanisms that stabilizes the amplitude of the initially rising HF-resonator voltage:

1. the amplification of the 'amplifier' (here the JFET) decreases, and
2. the damping of the resonator increases.

The first mechanism, an automatic gain control, is desired. The second one, the damping, is disastrous for the noise performance because it decreases the Q of the resonator.

Automatic Gain Control

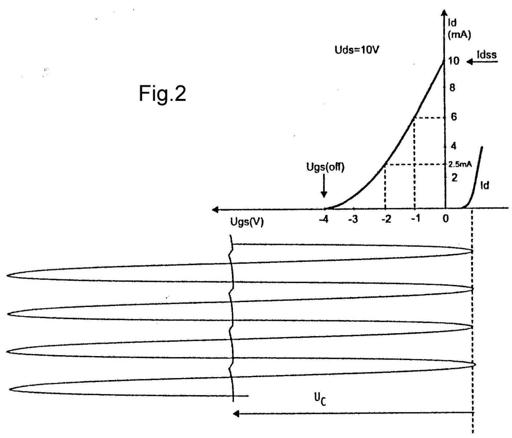


Fig.2

How does the automatic gain control take place in the circuit of fig.1? In fig.2 is shown how the FET attains into class-C. The larger the AC-voltage becomes the smaller the time per period will be in which the JFET conducts. Ergo, the amplification decreases with the amplitude. This mechanism is due to the gate-source-diode in the JFET, the resistor R_l and the condensers C, C'' and C'. It works as with a tube!

But....... in the Clapp oscillator of fig.1 this will be not the only mechanism. The resonator will also be damped by the drain-source-impedance if the drain-source-voltage (U_{ds}) drops down the pinch off voltage (Up), typically 4 volt with FETs like a J310.

Drain-Source-Impedance

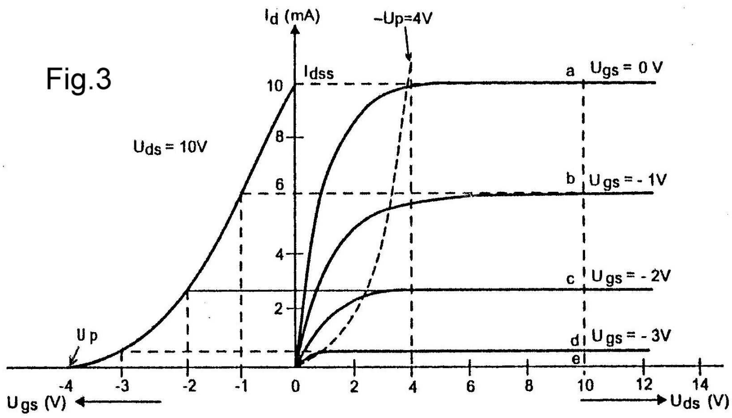
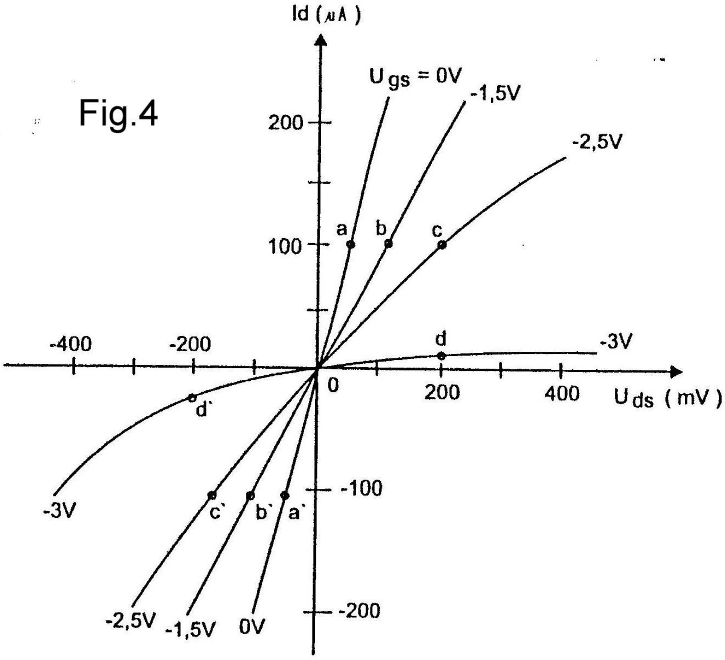


Fig.3

Every active element, bipolar transistors, FETs and even tubes, do have a pinch off point. In fig.3 the curves of a J310 are shown. The steeper the slope of the I_d-U_{ds} curve, the smaller the drain-source-impedance will be.

Fig.4



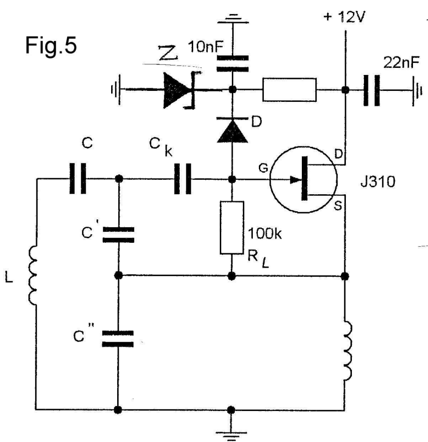
In fig. 4 the details of these curves around U_{ds} = 0 volt are shown. In this region the drain-source-impedance could be as low as a few hundred ohms. Be aware that this low impedance is in parallel with C" and thus damps the resonator in the peaks of the resonator voltage. (Due to the configuration of a JFET, the pinch off voltage (Up) has the same absolute value in the I_d -U_{gs} curve as in the I_d-U_{ds} curve.)

Damping by drain-source-impedance

Damping takes place if the AC-amplitude of the drain exceeds the DC supply voltage (U_{bat}) minus the pinch off voltage (U_P), so if $U_{ds} > U_{bat} - |U_P|$.
In our Clapp oscillator the drain is grounded for AC so that $U_{ds} = U_{0s} = -U_{s0}$. With a supply voltage of e.g. 12 volt (and a $|U_P|$ = 4 volts) this means that the drain never should exceed 8 volt or the gate never should exceed 8,7 volt, supposing the gate-source-diode starts conducting at 0.7 volt.

Remedy against damping

Fig.5



Add an 'extra automatic gain control' (extra agc) as shown in fig. 5. The diode D (a small Schottky diode as the BAT81, a silicon diode only makes things worse!) and the zener diode Z with the 10 nF decoupling, prohibit the gate to exceed 8,7 V! The relevant capacitor C_k will be discussed later. When the diode D comes into conduction (Schottky: 0.3 volt), the FET will be forced further into class C without noticeable damping on the resonator. ***This is totally different from the Schottky as clamping diode in the literature eg. Ulrich Rohde***.
One of the first remarkable effects of this 'extra agc' is that the frequency and the amplitude of the oscillator output (at the source) becomes independent of the supply voltage!
Is that all? No, there is more....

AM to FM conversion

Noise in an oscillator consists of AM-noise-modulation and FM- or PM-noise-modulation (phase noise). AM-modulation often does not harm the noise quality because the oscillator will be followed by a double balanced mixer (DBM) in radio applications or a ‘squarer’ in case of clock generators in digital equipment. In both cases the amplitude will be compressed.

What *does* harm is any conversion from AM noise into phase noise *inside the oscillator*. In my experience *this phenomenon is even more serious than damping of the resonator*.
This can only occur in non-linear elements.

Remedies against AM to FM conversion

In our oscillator these non-linearities only could be found in the active element: the JFET in this case. Particularly the voltage dependent parasitic capacity between drain and gate (C_{dg}) and between gate and source (C_{gs}) are the malefactors. Such capacities become larger with lower voltages over them.

Keeping the FET in saturation, eg. keeping the $U_{ds} > |U_P|$, avoids harmful variations of C_{dg}. This is what the 'extra agc' already does!
The 'extra agc' also prevents the voltage over C_{gs} to become zero or even +0.7 volt (the junction diode in the JFET no longer conducts!). It is not so easy to predict to which negative voltage the gate will be driven but the C_{gs} of a J310 enlarges from 6 pF to 9 pF with U_{gs} running from -5 to 0 volt. At +0.6 volt C_{gs} is more than 30 pF!
So, the 'extra agc' kills two birds with one stone: the <u>damping</u> and the <u>AM-FM-conversion</u>.

The functions of C_k

At first sight, C_k could be omitted. There is no 'DC-reason' for it. However, if we take C_k about 15 pF[1], the non-linearity of C_{gs} will be reduced.
Moreover the *bandwidth* of the agc enlarges with this 15 pF and R_l = 100 kΩ to 100 kHz! This means that the low frequency AM modulation components below this frequency will be reduced, so that much less AM to FM conversion will occur. C_k also kills two birds with one stone!

Be aware that without C_k, the diode D would be a 'clamping diode' over the resonator. In the literature one will find applications on this principle together with varicaps. A clamping diode also kills AM-components but adds damping to the resonator! The enhancement of the noise performance with the extra agc, compared to a clamping-diode, is *more than 15 dB!*

Tuning

Up till now the tuning of the oscillator has been left aside. Tuning could be implemented with since decennia well known mechanical means as permeability tuning or variable capacitor(s), so I will not dig too deep into this subject, the more a different phenomenon presents itself: **microphonics.** This is so bad that it overwhelms all other noise sources in the lower frequency regions.
The only way to circumvent this is tuning with varicaps or changing the permeability of magnetic material (by saturation) in the resonator coil. Both methods are very unpopular because of their non-linearity, *introducing AM to FM conversion!* What to do?

VCO's

In frequency synthesizers, Voltage Controlled Oscillators (VCO's) are used.

---

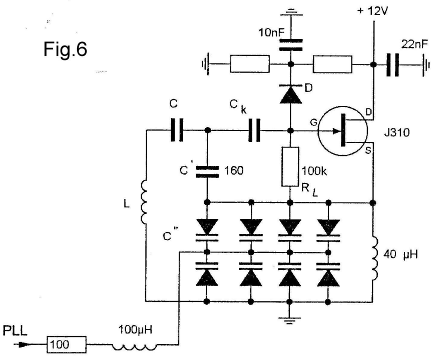
[1] don't take C_k too small because of the voltage devision C_k and C_{gs}. If you take C_k = 7 pF then the HF-voltage over C' and C'' will be twice U_{s0}.

Apart from microphonics, mechanical tuning in a PLL systems is unacceptable because of its delay. Also loop stability could be a problem.

Varicaps

Varicaps are unpopular because of there internal HF-resistance, causing drop of resonator quality (Q), and their nonlinearity: the change of the capacitance as a function of the tuning voltage is far from linear which could be corrected by an external circuit. Worse however is the HF-nonlinearity causing AM to FM conversion. The internal serial resistance could be decreased by connecting a number in parallel. The HF-nonlinearity will be decreased by using a 'double varicap', eg. two varicaps in a capsule with the cathodes connected to each other. Some of these are designed for oscillators as the Philips BB204G or the SMD version: BB804. They do not really solve the problem but are better than the single ones. Never use the varicap at too low tuning voltages and don't apply too large HF voltages on them. This is in contradiction to other low noise performance prescriptions!
Let be clear that an oscillator with varicap tuning always produces more noise than a not tuned optimized free running oscillator as in fig. 5. **But**, of all tuning methods, varicap tuning is the best (and most simple) method if microphonics is also taken into account.

Fig.6



In fig. 6 a circuit for a varicap tuned oscillator is shown. The biassing of D is lowered so that the source swing is about 4 volt peak to peak which has been shown up reasonable with varicaps.
In a professional measuring setting became clear how great the noise performance of a varicap-tuned Clapp oscillator is with this 'extra agc'! Even more surprising was the reproducibility of this circuit. The VCO on 13 MHz in fig. 6 performed: -145 dBc/Hz@10kHz and -140 dBc/Hz@1kHz.

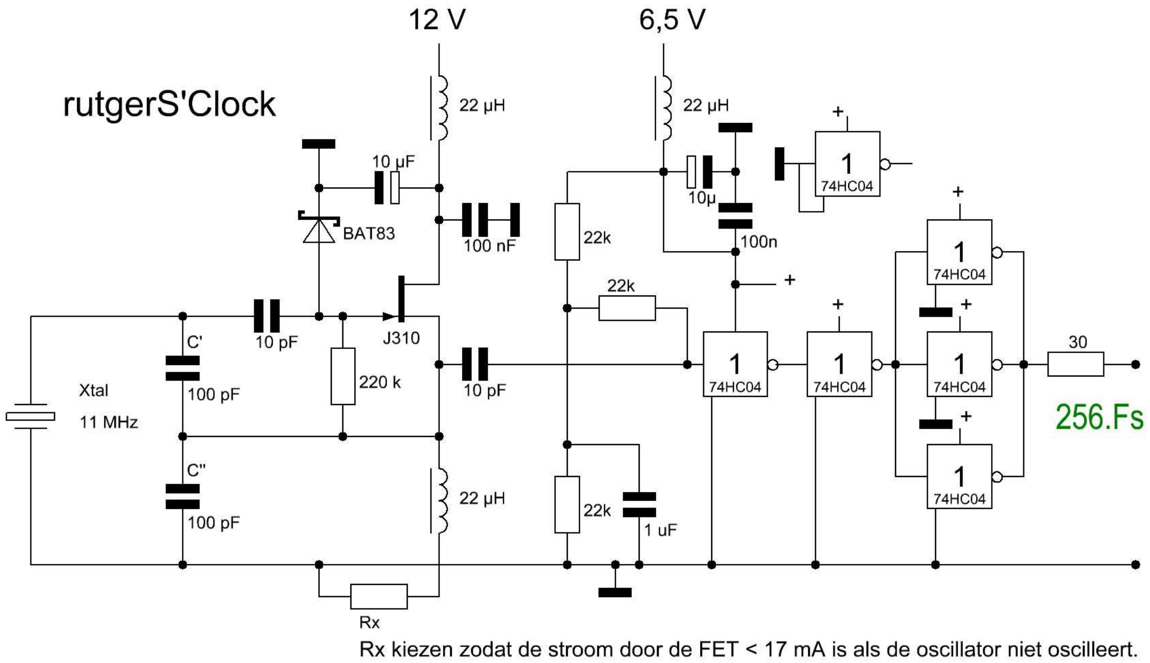
Magnetic Material

The oscillator contains at least two inductors: L in the resonator and the choke between source and ground. If magnetic material, as iron-powder or ferrite, has been used, its µ will be influenced by magnetic stray fields of mains transformers causing phase noise at double the mains frequency which will not be suppressed by the 'extra agc'. One could better use an air coil for L and an SMD choke. There are small SMD chokes with not too much resistance (< 2 Ω) which are much less sensitive to stray fields because of their small dimensions.

Xtal oscillators

In digital audio applications jitter on the clock signal which drives ADC's and DAC's, heavily determines the audio quality. Jitter is phase noise in the time domain.
The master clock is always a Xtal oscillator. Following apparatus mostly are equipped with a VCXO in a PLL system to synchronise the clocks to each other.
Simply replace L and C in fig.5 by a Xtal to get a Xtal-controlled oscillator. The noise performance of such an oscillator is some 20 dB better than that of the best free running LC-oscillator because of the excellent Q of Xtals, if Xtals not smaller than those in HC-18/U are used. Even here the 'extra agc' yields better jitter figures (down to < 1 ps [pico seconds]).

The only trouble with Xtal oscillators is, again, microphonics! There is a tremendous difference between one Xtal and the other. There are trade marks which are absolutely unusable.
A great deal of this microphonics consists of AM-components which will be effectively suppressed by the 'extra agc'. The FM-components however are not suppressed so that even less chock sensitive Xtals should be loaded, be connected with flexible wires to the rest of the circuit, and be supported by a soft plastic foam. Eventually the whole oscillator should be put in a solid box.
Xtals cannot handle too much power. Therefore the biasing of the BAT83 should be left out.



The Xtals are sorted out from a batch of special polished crystals. This polishing does not really enlarge the Q or lower the ESR but prevents noise-eruptions!

Clock-Oscillators

Equipment in digital audio installations will be provided with an XO. Eg. a CD-player is controlled by a Xtal oscillator. This oscillator must directly control the clock-input of the DAC (preferably a PCM1792). From many listening sessions became apparent that the close in noise (0.1 - 10 Hz from the carrier) is responsible for the audio quality: the intelligibility, brightness of the sound and the image of the soundstage. Phase noise at >100 Hz from the carrier affects the audio signal to noise (S/N) ratio. So, a very high Q of the Xtal is **no longer** the measure in clock oscillators! Therefore an AT-cut Xtal will satisfy the more of the much lower ESR. Put as much current into the resonance circleit as possible before noise-eruptions arise. Often the Xtal will be used outside its specs concerning maximum permissible power. In clock oscillators the exact frequency is hardly of interest (>300 ppm) so the drift in time. (Mind that no human being is able to here the difference between 1000 and 1001 Hz, which is 1000 ppm!)

Dissipation in Xtal

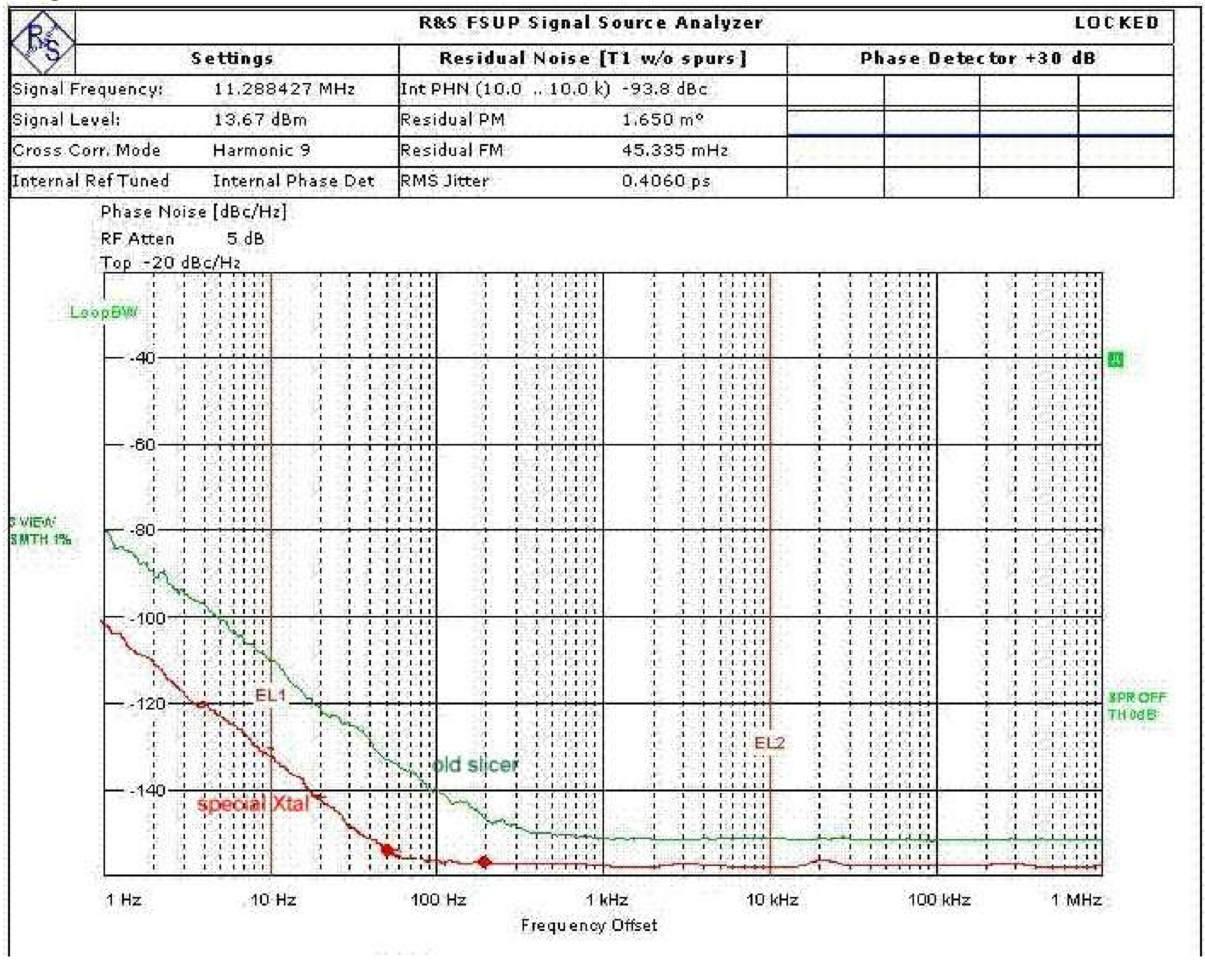
How could the dissipation in an Xtal be stipulated? Well, in the rutgerS'Oscillator the HF-output voltage is about 4 V_P = 2.8 V_{RMS}. This means a circle flow of:

$I = 2.8 \cdot \omega C'' = 2.8 \cdot 2\pi \cdot 11 \cdot 10^{6} \cdot 100 \cdot 10^{-12} = 194 \cdot 10^{-6}$ A = 19.4 mA.

If the ESR = 7 Ω (an average value) the dissipation will be $I^2 \cdot 7$ = 2.6 mW !!

Results

In the plot below the results of the rutgerS'Clock has been displayed. The green curve is with a LT1016 as squarer and the red curve with a 74HC04 as in the diagram above.



Remarks with the figures:

Fig.1: The Clapp oscillator with the JFET J310.

- C ...(pF) ≈ $500/f_0$, if F_0 is the resonance frequency in MHz.
- C' = C" ≈ 4.C
- L ...(µH) from $40.f_0^2.L.C_0=1$ with $C_0 = 2C/3$ in this case.
- $R_l \geq 100$ kΩ
- 'choke' ...(µH) ≈ $200/f_0$ if f_0 is in MHz.

Fig.2 : The I_d-U_{gs}-curve of a small JFET in class-C. The negative voltage U_c is obtained by the current through the junction diode and the leakage resistor which charges C and C'.

Fig. 3: An I_d-U_{gs}-curve together with the I_d-U_{ds}-curves. In both the pinch off voltage U_P (typically 4 volt) has been indicated. The pinch off voltage follows the dotted curved line with the various gate voltages (U_{gs}). Left from this dotted curve is the so called linear area in which the drain-source-impedance is (much) lower than to the right of it (the so called saturated area).

Fig.4: The I_d-U_{gs}-curve in detail near the origin. With small values of I_d and U_{ds} the drain-source-impedance is very small. The steeper the curve, the smaller the impedance. Here these values vary from 500 - 16,000 Ω.

Fig.5: The Clapp oscillator completed with the 'extra agc' consisting of C_k, the Schottky diode D, the zener-diode Z, a resistor and an HF-decoupling of 10 - 1000 nF.

Fig.6: The Clapp oscillator tuned with varicaps as in a VCO.