

## Design approaches for oscillators in low microwave bands

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### Abstract

Several design procedures for oscillators are proposed and compared with commercial CAD tools and finally with measurements of fabricated voltage controlled MMIC prototypes. All of the proposed design techniques are easy to implement in any CAD package, or even to code in any Language. They provide, not only appropriate initial values for the components in more complete simulations, but also accurate final results. Measurements permit the validation of the whole design process, the models and the technology used. The Philips GaAs ER07AD process (Limeil, Paris) has been employed.

### Introduction

GaAs Monolithic Integrated Circuit technology is suitable for the construction of voltage controlled local oscillators operating in this band because of the advantages versus Si technology, specially in terms of front-end complete integration (plus LNA, mixers, prescalers, etc.) [1].

### Basic Topology

The loop feedback oscillator topology used to apply the techniques is the Colpitts structure. Nevertheless, it is extended to the same basic topology, but in a symmetrical differential structure. This type of harmonic oscillators provides more stability and less phase noise than other types of oscillators (e.g. relaxation). Two separate blocks can be considered: An active non linear two-port, which provides the gain to the loop, and a filter or resonator (another two-port). Gain Block is carried out using a common gate scheme, which increases instability. Positive feedback, through an inductor between gate and ground may be added, if it is necessary. A common gate stage provides bigger voltage gain than common source or common drain stages. The filter includes a capacitive divider with a varactor diode.

### Methods

Three methods are proposed for the design of oscillators with a feedback loop structure (both, single ended and differential):

- A. Simplified Computations
- B. Invariant impedance transformation
- C. Open Loop Oscillation Analysis

A. Preliminary calculations based on Barkhausen oscillation criterion are presented. The non linear devices, MESFET transistors, have been represented by their small signal models. Simply by coding some easy equations, this procedure permits the designer to fix the initial values of the main components, according to the desired frequencies for oscillation. The main capacitors loading each node have been considered including non linear variation of the varactor capacitance. In a feedback loop oscillator, voltage gain must be equal to unity in magnitude with null phase. This criterion has been applied to the equivalent circuit of the oscillator.

Some aspects must be highlighted:

- In the most general case, two buffers have been included, one to extract signal for the 50Ω load (source follower) and another to feed a prescaler (common source) [3], to synthesize the oscillator. In this way, integration is increased, compared to using an external coupler.
- If the signal is extracted at the output of the filter the purity of the signal will be greater.
- The use of a buffer decreases the pulling and increases the power given to the load.
- The RF ground points may be real or virtual. This means that the analysis is also valid for the same basic structure, but in symmetrical and differential configuration [4].

B. Invariant impedance transformation is based on the idea of loop opening to present the same impedance to each port as is presented in closed loop normal operation. This method is small signal model based.

In the scheme of fig. 1 the reflection coefficients  $\Gamma_{in}$  and  $\Gamma_{out}$  are defined. From the left side, the reflection coefficient is  $\Gamma_{in}$  with the two-port network loaded with the same  $\Gamma_{in}$  on the right side. From the right side, the coefficient seen is  $\Gamma_{out}$ , with  $\Gamma_{out}$  loading the left side. For this reason it is called the impedance transformation method. Once the scattering parameters of the non linear device and the cascaded resonator are computed, the equations for calculating the reflection coefficients of two loaded port networks are applied.

$$\Gamma_{in} = S_{11} + \frac{S_{12}S_{21}\Gamma_{in}}{1 - S_{22}\Gamma_{in}} \quad (1)$$



$$\Gamma_{out} = S_{22} + \frac{S_{12}S_{21}\Gamma_{out}}{1 - S_{11}\Gamma_{out}} \quad (2)$$

The solution for  $\Gamma_{in}$  and  $\Gamma_{out}$  verifies the condition expressed in fig. 1 around the oscillation frequency. The trivial solution is  $S_{11}=0$ ,  $S_{22}=0$  and  $S_{12}=S_{21}=1$  (phase  $0^\circ$ ). This means that the transmission matrix would be the identity. This solution is valid only if each one of the components of the feedback loop is perfectly matched to the reference impedance.

Fig. 2 shows frequency versus variable capacitance relationships calculated through  $S_{21}$  null phase, the invariant impedance transformation and the small signal oscillation test (HP-MDS).

C. Open Loop Oscillation Analysis is based on the same idea, in this case, building a chain of the two basic elements of the oscillator, gain block and filter, repeated several times. This idea has been applied in a more model-based manner in [2]. This is the most powerful of the procedures, suitable for extension from small signal to large signal. It permits the designer to obtain, not only the frequency of oscillation, but the power levels too. Through a simple idea, all the procedures for optimizing an amplifier may be extended to oscillators.

When designing negative impedance based oscillators, the condition for the oscillation to initiate is that the product of the reflection coefficients looking towards the linear part (RES,-REsonator-) and looking towards the non linear part (diode, feedback transistor, . . . ,: NLD, -Non Linear Device-) must be greater than unity in magnitude and phase zero (fig. 3). When, after starting and growing, the oscillation reaches the steady state, the magnitude of the product equals unity with phase 0.

The device line procedure is based on this concept and allows the designer to accurately know the signal level and the oscillation frequency.

This requires two different calculations. One is the reflection coefficient versus frequency of the linear part and the other is the reflection coefficient versus input amplitude of the non linear part. When both complex numbers are equal, the frequency and amplitude of the oscillation are found. Note that the dependence of the impedance of the non linear part on frequency is ignored.

This classic method previously described is not suitable to analyze the oscillation in feedback structures. In this case the problem consists of two two-port networks cascaded and feedback, not two one-port networks, one opposite the other (fig. 3). The network containing the non linear device acts as an amplifier, and the linear network is the frequency selective component. Here the confronted reflection coefficients depend on the loads. One way to solve this problem is to break the feedback loop and build a chain with an adequate number of the same repeated elements. In this way each element would experience the same impedance loading as if it were situated in the feedback

loop (fig. 4).

Resulting from this basic idea, a linear analysis and a non linear analysis may be applied to the open chain structure in the same way as amplifiers are analyzed.

Barkhausen oscillation criterion may be applied to small signal, calculating the voltage gain of the linear and the non linear part, loaded with adequate impedances (supplied by the same elements, repeated both sides of the elements chosen to evaluate the gain).

The product of both gains (linear part and nonlinear part) must be greater than one in magnitude, with phase 0, at the oscillation frequency.

For large signal analysis, the open chain of repeated elements is fed with a power source, with a frequency around the null phase frequency found in the previous analysis. The amplitude of the source is varied until voltage gain of one and phase zero is achieved in consecutive stages. This means that the voltage waveforms in two homologous consecutive nodes are equal and can be superimposed perfectly with the same amplitude and the same phase.

The chain is built by cascading repeatedly the two basic elements: the nonlinear part (gain) and the linear part (frequency selectivity).

The nodes that are located in the same port of the basic elements, but in different positions in the chain are called "homogeneous nodes".

This method is also very interesting when the available CAD packages do not include specific tools for oscillation analysis.

The method was used to design the Colpitt's oscillator. The results are compared with the ones supplied by a small signal S-parameters oscillation test and harmonic balanced oscillation analysis (HP-MDS). Fig. 5 shows the frequency versus varactor capacitance curves predicted by the simplified calculations, the small signal oscillation test (HP-MDS) and the open chain small signal analysis.

The results of different analyses are shown to validate the large signal extension of the method, based on the small signal results. For a 1pF capacitor fixed in the varactor diode, the open chain large signal analysis was performed. Power supplied to the chain and frequency was varied (the latter around the value predicted by the small signal analysis) to achieve perfect superimposed waveforms in consecutive homologous nodes.

The shapes of the waveforms are shown in fig. 6, after performing the Fourier Transformation. In fig. 7 the waveform predicted by HP-MDS harmonic balance for this case is shown. If both figures are compared, it makes the efficiency of the method obvious. There is a coincidence in amplitude and in phase.

The number of repetitions of the main elements in the chain should not be too high (4-8). Numerical convergence problems are avoided by supplying less power to more stages. In this way, the signal grows until it limits itself at a certain stage. This option is considered more suitable than the other possibility which consists of supplying more power to a shorter chain, saturating the gain.



### Fabricated Prototypes

Using the procedures previously proposed and a HP-MDS simulator, different prototypes of both oscillators, single ended and differential, were designed and fabricated (chip size  $1 \times 1.5 \text{ mm}^2$ ) using the ER07AD process (Philips, Limeil). Measurements were performed on wafer, obtaining the tuning characteristics, band covered (1.75-2 GHz, single ended Colpitts oscillator, 2.25-2.8 GHz differential oscillator), power versus frequency curves (6-7 dBm each output, mean value for both types, single ended and differential), harmonics power and phase, phase noise estimate, waveforms, highest modulating frequency, starting time etc.. (See fig. 8-11).

### Conclusion

Simple methods for the design of oscillators have been proposed and validated by comparisons with standard commercial tools and with measurements. These methods provide a useful insight into the loop oscillator topology. They allow the accurate fixing of initial and, even, final values.

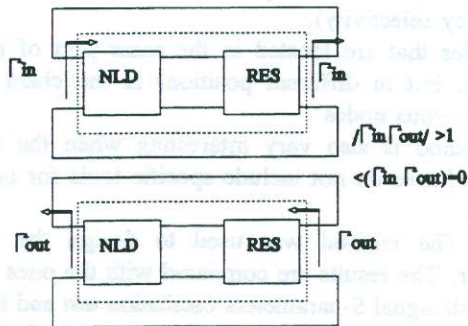


Fig 1. Invariant impedance transformation.

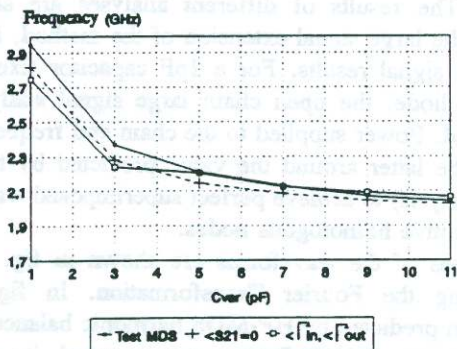


Fig 2. Frequency versus capacitance with the MDS test, with invariant impedance transformation and with the null phase  $S_{21}$ .

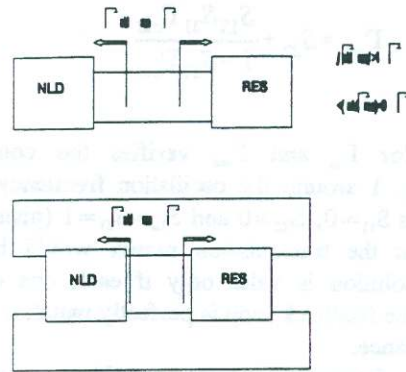


Fig 3. Negative impedance and feedback oscillation.

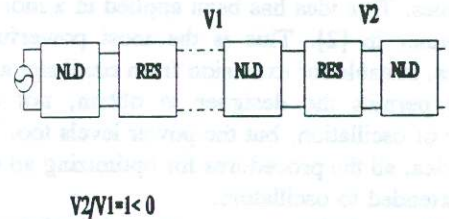


Fig 4. Feedback Oscillation in open loop.

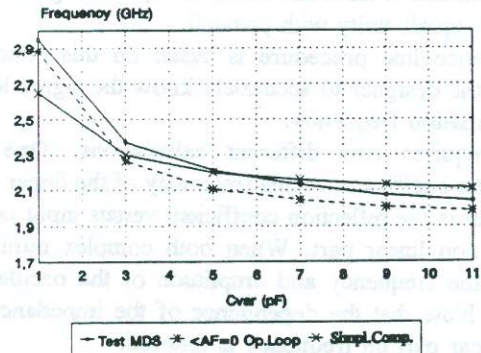


Fig 5. Simplified computations, small signal test (MDS) and open loop analysis for the Colpitts oscillator.



