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Crystal controlled oscillators in the UHF-range by PLL-technique

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1. Introduction

Modern communication requires highly stable frequency sources at elevated frequencies up to 1 GZ and above with high spectral purity and low phase noise. Therefore the VHF/UHF frequency has to be derived from or locked to a crystal oscillator at lower frequency. This can be done either by frequency multiplication or by phase-locked loop (PLL-) techniques.

The paper compares the possible solutions and describes a modular approach to a family of crystal controlled oscillators such as PXO's, VCXO's and OCXO's in the VHF/UHF-range.

Results for a TCXO at 1.2 GHz and a VCXO at 278 MHz are presented.

2. Alternative concepts

2.1 Frequency multiplication

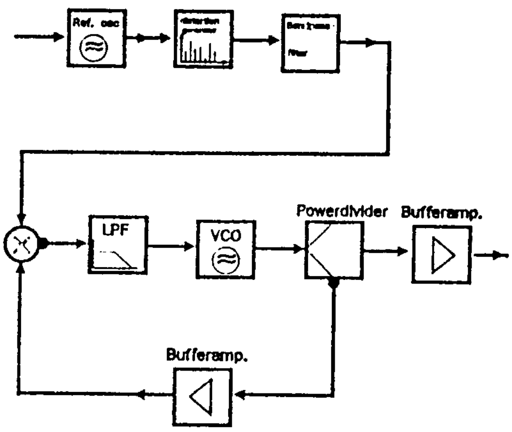
The simpliest principle for the generation of stabel VHF- or UHF-signals is the successive multiplication of the output frequency of the crystal-controlled reference oscillator.

The higher the final frequency, the more complex become the necessary efforts for effectively generating and filtering of the desired harmonics. A large number of tuned L-C-filters or crystal filters (or other types of filters) are required, making the adjustment work of the whole unit more and more tedious. The output spectrum shows a whole "fence" of unwanted frequencies (harmonics and subharmonics), whose attenuation is determined by the amount of selection means, the Q of the filter elements and the accuracy of the adjustment. The advantage however is, that the phase noise is not much degraded and is mainly determined by the reference oscillator itself, the multiplication factor, and the inherent noise of the frequency multipliers.

In the PLL-based concepts, a voltage controlled oscillator (VCO) based on an oscillator with lumped L-C-elements, stripline components, SAW resonators, or ceramic resp. dielectric resonators, is locked to the crystal-controlled reference oscillator. Two alternative approaches may be used: harmonic sampling or PLL with frequency division.

2.2 Harmonic sampling

The schematic diagram is given in Fig. 1. Strong harmonics of the reference oscillator output signals are generated by distortion into very short pulses. The desired harmonic is filtered out and fed to a phase detector, in which its phase is compared to the signal of the VHF/UHF VCO. Through a low-pass filter, the output of the phase detector controls the VCO and locks it to frequency.



The advantage of this method is, that the phase loop operated on a high frequency, and therefore the response characteristics can be extremely fast, and the phase noise close to the carrier is improved.

The disadvantage is, that good filtering of the desired harmonic is necessary, as the unwanted harmonics appear as side lines in the output spectrum of the VCO. For higher frequencies, much circuitry is necessary for the frequency multiplication.

In Fig.13 the noise sidebands of the VCO itself are shown, both in free-running mode and when it is locked to the crystal oscillator.

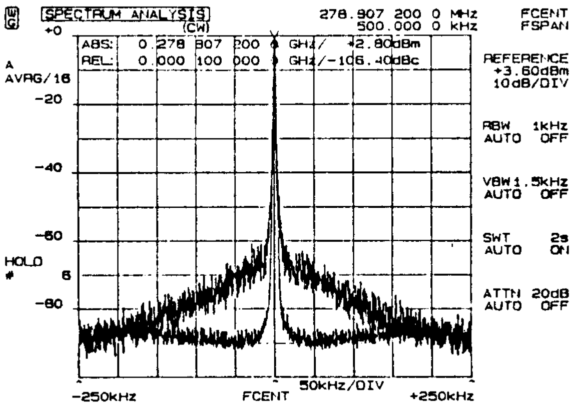


Fig.13: VCO noise sidebands free-running/locked mode

The dynamic behaviour of the 278.528MHz VCXO frequency is very important, because in the application the unit is integrated into an other PLL-loop. Fig.14 displays the over-all time response of the output frequency for a pulling voltage step from 0.2V to 2.3V. It can be seen that the response is very smooth.

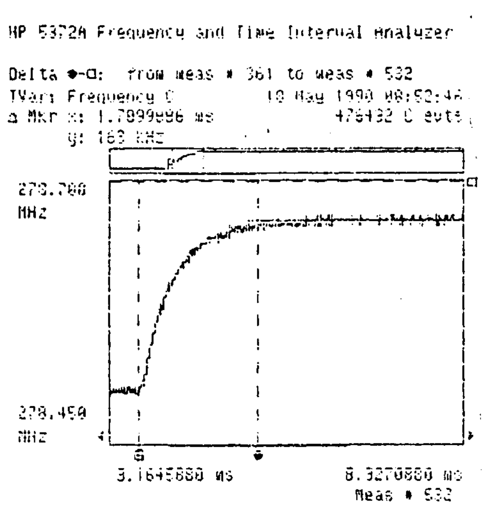


Fig.14: time responce of the output freqeuncy to a pulling voltage change

Finally Fig.15 shows the frequency response of the modulation, i.e. how the frequency deviation of the FM signal changes at higher modulation frequencies. The 3dB corner (modulation bandwidth) is above 8kHz, which is better then the system requirements.

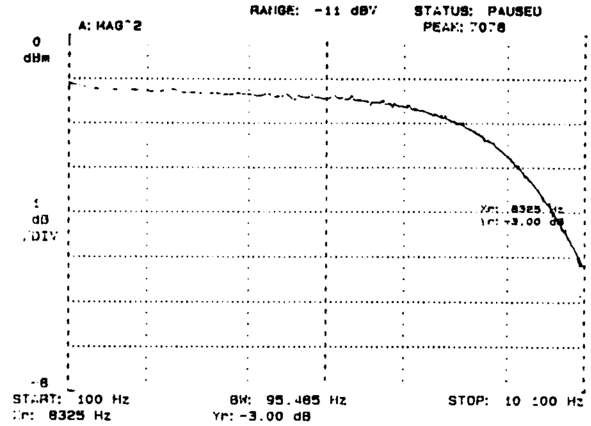


Fig.15: frequency response of the modulation

2.3 PLL with frequency division

The principle is depicted in Fig. 2. The phase detector input is either connected directly to the reference oscillator or is fed by the reference frequency divided by factor T. This frequency is compared to the VCO output frequency divided by a larger factor N. Therefore the output frequency of the VCO is locked to

$$f_o = f_{Ref} * N/T$$

Advantageous is, that the phase detector loop works on a rather low frequency, and thus can be realized by commonly available integrated circuits. For the high frequency division by N also a variety of standard ICs is available, mainly based on ECL resp. GaAs technology.

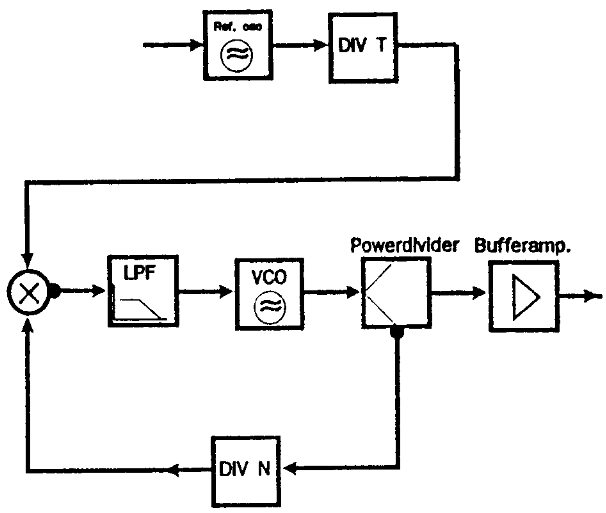


Fig. 2: PLL with frequency division

The output spectrum shows mainly two sidelines at fo+-f_{Ref}/T. In poor designs, also several multiples of f_{Ref}/T may occur.

The disadvantage is, that the phase-locked loop works at a rather low frequency, which yields a slower response characteristic. The phase noise of the reference oscillator is degraded by the factor N, the overall phase noise is strongly influenced by the control loop design.

3. Phase noise considerations

The influence of different noise sources on the phase noise performance can be analyzed by insertion of noise sources into the phase control loop, as shown in Fig. 3.

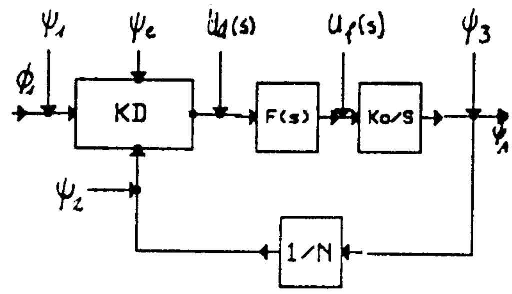


Fig. 3: Noise sources in the phase control loop
K_D is the transfer constant of the phase detector, F(s) is the frequency response of the loop lowpass filter, the Psi-values are the phase fluctuations of the different stages.

The phase fluctuation at the output of the PLL-circuit can be derived from this picture to be

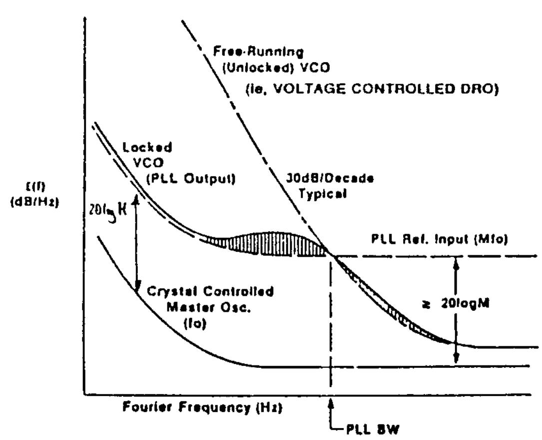
$$\psi_A = (\psi 1 + \psi 2 + \psi_e) \cdot N \cdot \frac{1}{1 + 1/(\omega_n^2 \tau_1) \cdot s + 1/\omega_n^2 \cdot s^2} + \psi 3 \frac{N s + \tau_1 s^2}{K_D K_O \cdot N + N \tau_1 s}$$

The first part of this expression shows a lowpass characteristics. Noise at the frequency control input port of the VCO appears at the output with limited bandwidth. The phase fluctuations of divider, mixer, and reference oscillator are summed up and a factor, which increases this term proportionally. The lower the inherent phase noise of these components, the lower is the overall noise. The noise contribution of this term is also proportional to the frequency division factor N, which therefore should be as low as possible. The phase noise close to the carrier, within the loop bandwidth of the PLL, is mainly determined by the noise of the PLL components, especially by the close-to-carrier phase noise of the reference oscillator.

The second part of the formula represents a highpass characteristics. The phase noise at Forier frequencies larger then the loop bandwidth are mainly governed by the VCO. Therefore it should be realized with a lownoise circuit design using a high effective-Q of the resonator element.

Furthermore it can be seen from the formula, that a low pole frequency w_n is advantageous for good phase noise performance.

Typical phase noise spectra for a free-running and a locked VCO are given in Fig.4.



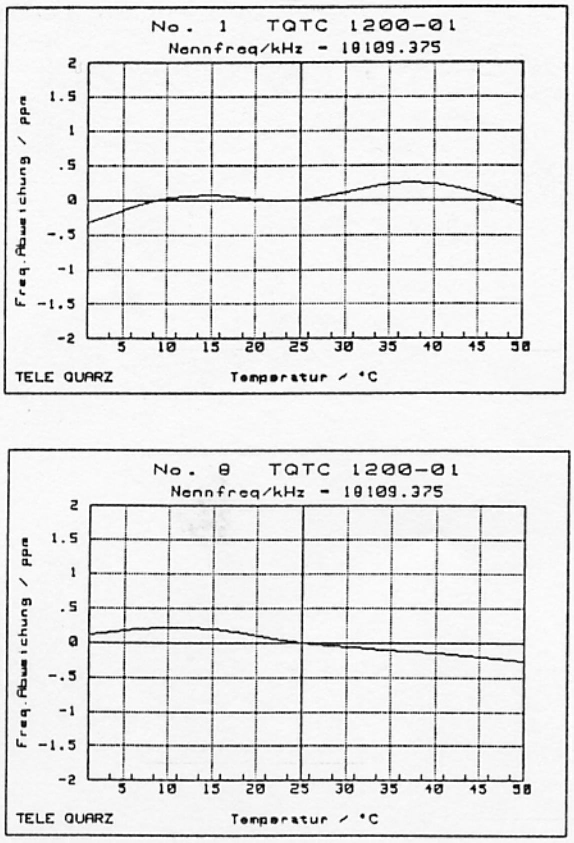


Fig. 8: frequency stability vs. temperature 1.2 GHz TCXO

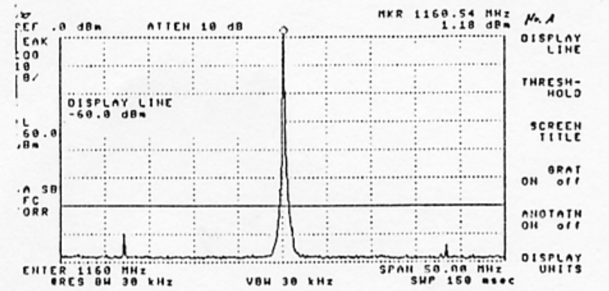


Fig. 9: Output spectrum of the 1.2 GHz TCXO

Another example is an VCXO at 278.528 MHz, used for frequency multiplex applications. In this case, the whole circuit, including all components, could be placed on one pc-board 33mm*24mm. Thus the housing could be reduced in height to 12.8mm.

The VCXO works with a supply voltage of -5.2V and draws 70mA. It has two complementary ECL outputs with rise and fall times of approx. 350 ps. The frequency pulling range is +-200 ppm +-10%.

The 278 MHz-VCO uses a tuned LC-circuit, which is optimized for low phase noise.

In Fig.10 the measured pulling characteristic is shown.

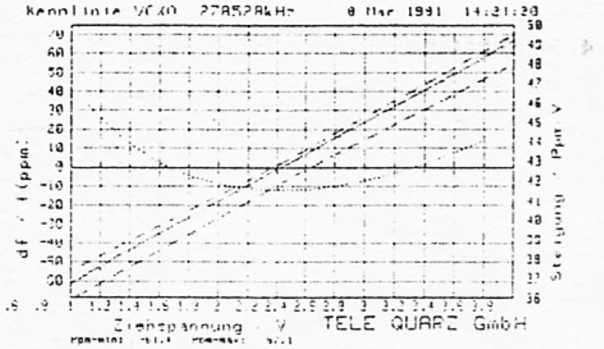


Fig. 10: Pulling characteristic 278.528 MHz VCXO

In the output spectrum, the lower side line at fo-fRef is attenuated only by -54 dB, whereas the upper side line is 70dB down. This is due to the compact construction of the unit.

The first harmonic is 32dB below the carrier (see Fig.11).

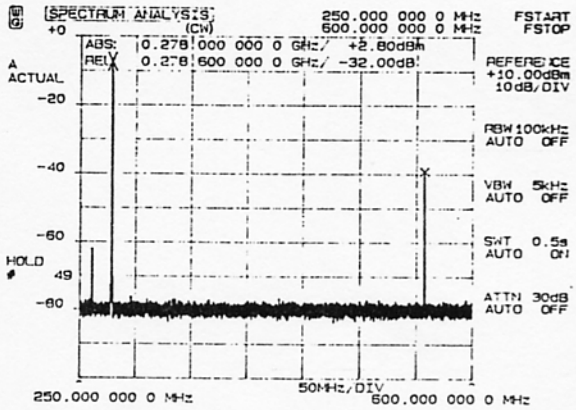


Fig.11: output spectrum VCXO 278.528 MHz

Fig.12 is a close-up view of the noise sidebands of the carrier frequency taken from a spectrum analyzer.

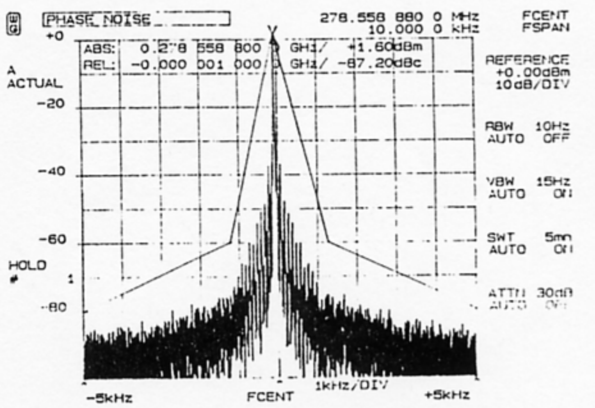


Fig.12: Noise sidebands of the 278.528MHz signal

4. Realization

Based on the PLL technique with frequency division, a modular approach was developped which allows to realize crystal-controlled oscillators of different kinds in the VHF-/UHF range up to 1.3 GHz. The upper limit is currently only set by availability of inexpensive frequency divider IC's and the maximum recommended power dissipation in a miniaturized package, which can be accepted without degradation of stability and warm-up characteristics.

The basic unit in this approach is a module consisting of the phase detector, the lowpass filter, the VCO with its output stage, and the VHF/UHF frequency divider.

This module, which is located on a pc-board of 33 mm *24 mm, can be combined with any suitable reference oscillator, which may be a PXO (packaged crystal oscillator), a VCXO (voltage controlled crystal oscillator), a TCXO (temperature controlled crystal oscillator), a DTCXO (digitally compensated crystal oscillator), a TCVCXO (combination of TCXO and VCXO), or even an OCXO (oven controlled crystal oscillator). Thus, depending on the combination, we directly get a PXO, VCXO, TXCO etc. in the VHF-/UHF frequency range.
In this modular system, the complete unit is housed in a standard oscillator enclosure with the dimensions 36.1mm*27.2mm*19.4mm (L*W*H*). The VHF-/UHF-pc-board is directly mounted onto the inside part of the bottom plate of the oscillator enclosure. On top of this module, the second pc-board, containing the reference oscillator, is attached (see Fig.5). This oscillator can be selected out of a variety of existing oscillator models (PXO's, VCXO's, TCXO's etc.), which were already designed to fit into the same housing.

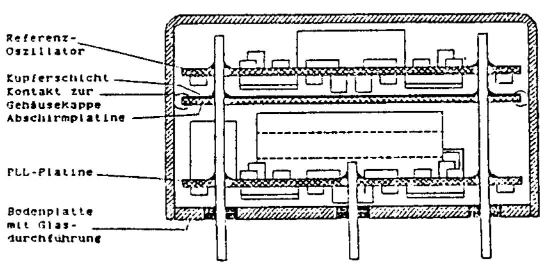


Fig.5: modular construction

Fig. 6 shows as an example the UHF-part of a TCXO operating at approximately 1.2 GHz.

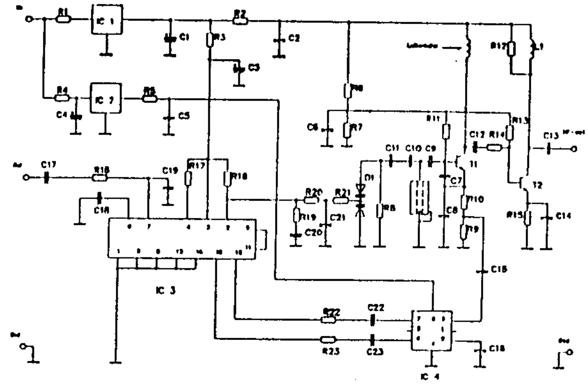


Fig.6: UHF part of a 1.2 GHz TCXO

The VCO is realized with a dielectric resonator with an open-circuit Q of approximately 1000. The temperature coefficient of the free-running VCO is shown in Fig. 7.

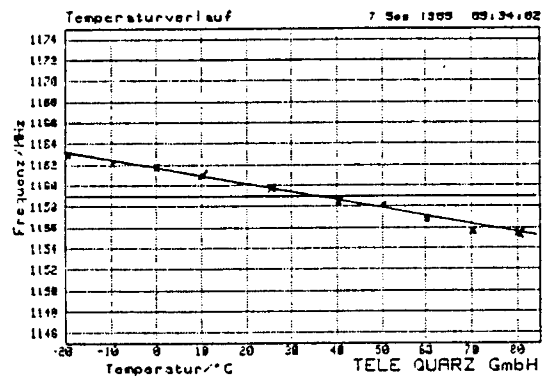


Fig. 7: temperature coefficient of the 1.2 GHz VCO (free-running)

The frequency divider is a two modulus prescaler in ECL technology.

The TCXO has a temperature stability of better than 0.5 ppm in 0°C to +50°C (other stabilities in other temperature ranges can be easily derived). The current consumption is 70mA at 15V supply voltage with an output signal of typical 0dBm.

Fig. 8 shows typical curves for the frequency stability vs. temperature. In Fig. 9 the output spectrum of the oscillator unit is depicted. The two sidelines at fo+-f_{Ref} are -70dB or more down, the spectrum far-off is extremely clear. The phase noise is below -100dBc at 100 Hz and above.