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# LOW PHASE JITTER IN L-BAND XO: FREQUENCY MULTIPLICATION OR REGENERATION

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***Abstract*- This paper presents the results of crystal oscillator (XO) development, which generates an output signal in the L-band. The conditions of BJT stage operation allow simultaneous forming, a fundamental mode of quartz crystal oscillation, as well as, considerable amplitude of required harmonic. It's known, that the interaction of a basic oscillation with its harmonics is a reason for additional phase shifts in an oscillating loop and stability decrease in stability of oscillator. However, these researches have shown, that use of a regenerative operation mode in oscillating stage on a required harmonics allows not only to gain sufficient amplitude of L-band signal, but it also allows us to realize a high loaded Q-factor on a fundamental mode of a quartz resonator. The obtained power spectral density of a phase noise $S_\varphi(1kHz)$=-110 dBc/Hz for 1 GHz oscillator output signal shows the advantages of the proposed method. It extends XO application range into L-band and allows to get phase jitter lower than 1ps for large jitter bandwidth.**
***Keywords*- crystal oscillator, L-band, frequency multiplication, regeneration**

## I. INTRODUCTION

Phase noise is critical in many modern communications applications, especially those employing high data-rate digital modulation schemes. For example, in digital links employing quadrature-amplitude modulation (QAM), different phase states represent digital bits. Excessive phase noise in the system can obscure these bits, resulting in an excessively high bit-error rate and possible loss of data.

Phase noise critical systems could be divided in two groups. The first group consists of signal sources, which are synchronized with a Stratum Clock. This includes XDSL, T1/E1, T3/E3, and OC-XX communications techniques. Oscillators based on surface-acoustic-wave (SAW) can provide sufficient low phase noise signal for these applications. The performance levels required in this case are in the 3 to 10 ps RMS jitter [1,4].

The second group consists of the applications, which use non-synchronized clock signals. It requires free running oscillators providing low jitter and high frequency stability signals. This includes point-to-point digital links, analog signal digitizing, server and workstation's processors seed clocks. The required jitter level should be in 1 to 5 ps RMS boundaries in the jitter frequency band from 100 Hz to 20 MHz, the frequency stability overall conditions (initial calibration, temperature, aging, etc.) should not exceed ±20 ppm in the operating temperature range [2].

A comparison of different methods for L-band signal generation (based on PLL, SAW, STW, XO) has shown, that a frequency transformation of a quartz crystal oscillator signal into L-band has superior overall frequency stability. The developed oscillator is based on the same technique of a harmonic selection, which was presented in [3].

The oscillating stage is a Colpitts circuit and it contains AT-cut "inverted mesa" quartz crystal resonator. The stage operates on a fundamental mode of a resonator or it's overtone in case of XO, which can be chosen in the range of 160-260 MHz. The oscillator stage contains a selection circuit, which is tuned on the required harmonic of the main oscillation. Further filtration and amplification of the signal allowed obtaining undesired harmonics and main oscillation suppression of more than 40 ÷ 45 dB with respect to the power of desired frequency signal. The developed XO can be easily transformed into VCXO, so it is suitable for use in local-multipoint-distribution system (LMDS), in clock cleanup/recovery applications, and other applications where clock signal is synchronized with received signal and where initial frequency tolerance is important.

## II. MAIN RESTRICTION OF XO PARAMETERS

A frequency multiplication is an inevitable part of a quartz crystal signal transformation into L-band. Since phase noise degrade with multiplication by a factor of 20logN, where N is a multiplication factor we should estimate a limit on multiplication factor to prevent clock jitter increase above a certain level, for example 1ps. Let's calculate a power spectral density of a phase noise $S_\varphi(f)$ of 1GHz oscillator which will correspond to this jitter restriction. We should consider phase noise on two essentially different time intervals: short term and long term. The first defines peak-to-peak jitter and the second determines the jitter on interval about 10÷100ms. That duration is commonly required by the protocols of modern communications systems [2].

Let's begin with estimation of "floor" level of a phase noise spectral density, which closely correlates with peak-to-peak jitter. It is possible to apply the common formula [5] to calculate phase jitter:

$$\sigma^2_{\Delta\varphi}(\tau) = 8\int_{f_{min}}^{f_{max}} S_{\varphi}(f\ )[sin(\pi f\ \tau)]^4\, df \quad (1),$$

if substitute τ =0.5 ns and dependence $S_\varphi$ upon frequency offset $f$ in that equation, but for our purposes we can use simpler expression from [6]:

$$\varepsilon_{ptp} = \sqrt{f_h S_\varphi(f)/2\omega_0^{\ 2}} \quad (2),$$

where $\varepsilon_{ptp}$ -half period jitter, $\omega_0$ - carrier frequency of a signal, $S_\varphi(f)$ - the power spectral density of phase noise on the 'floor', $f_h$ - the upper frequency in signal spectrum, $f_h$ = 2GHz in that case. The expression (2) gives a value $S_\varphi(f)$ = -140 dBc/Hz if peak-to-peak jitter equals 1ps.

We need to determine low frequency $f_{iow}$ in a jitter spectrum in order to estimate the required level of a phase noise spectral density close to the carrier. For many of the modern communications protocols it is required that $f_{iow}$=100Hz. Let's calculate a value of $S_\varphi(f)$ at frequency offset from the carrier $f$=1kHz. The function of the spectral density at a small frequency offset has 30 dB per decade slope and an integral (1) can be simplified to the following expression [6]

$$\varepsilon(\tau) = \tau\sqrt{\ln 2 S_\varphi(f) f^3 / f_0^2} \quad (3),$$

where $\varepsilon(\tau)$ - jitter on a time interval $\tau$, $\tau$- the observation time (in our case $\tau = f_{low}$ ), $f_0$ – the signal carrier frequency . The expression (3) gives a value $S_\varphi(1kHz)$ = - 110 dBc/Hz for clock jitter $\varepsilon$ *(10ms)* =1ps.

The modern transistors can provide noise floor of -165 ÷ -170 dBc/Hz , so we have a margin of 14÷17 dB, which can be allocated to the frequency multiplication operation. Hence, the factor of frequency multiplication can be limited to the value of 6÷8. Therefore, to produce L-band signal the fundamental mode of quartz resonators should be in the frequency range from 160 to 260 MHz.

The required level of the sub-harmonics and a spurious suppression in L-band signal can be evaluated by equations valid for a harmonic phase modulation. This evaluation has been done by the author in paper [7]. The obtained result shows that in order to attain phase deviation less than 0.01 radian (modulation index equals 0.01), the amplitude of the above-mentioned spectral components should not exceed -46 dBc.

## III. CIRCUIT DESCRIPTION

Simplified XO schematic for 1.0 GHz output frequency signal is shown in Figure 1.

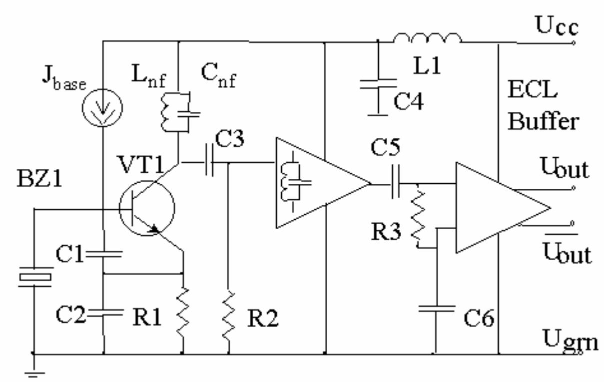


Fig.1. The oscillator schematic

The oscillator stage is a Colpitts circuit with a 166.6 MHz fundamental crystal. It is known, that the operation mode of the oscillator stage is the key factor in obtaining high amplitude of required harmonic. Two variants of the biasing stabilization are possible in the Colpitts circuit based on BJT transistor: to hold constant the base current, or the base voltage. In our case when the sixth harmonics was selected, the best signal quality was obtained with use of the current stabilization technique.

The collector load of the transistor oscillating stage is selecting circuit, for example the tank circuit, which is tuned on the sixth harmonic. To obtain a large amplification coefficient for a chosen harmonic, it is necessary to have large and high quality impedance of the collector circuit. However, for L-band signals the transistor stage works as a common-base stage. Therefore it is necessary to take into account feedback capacitance of the transistor for preventing self-excitation on the chosen frequency.

The oscillating stage mode in which it reveals regenerative behavior is optimum for an increase of the suppression of undesirable harmonics as well as for an increase of small signal sensitivity. According to a value 0.7pF of feedback capacitance of a used NE68530 transistor, and the values of capacitors C1, C2 (which are determined by the requirement of fundamental mode excitation) amplification coefficient $K_{amp}$ = 15 dB can be obtained, thus coefficient of regeneration should be not more than 5 dB. The obtained suppression of the undesirable harmonics and the carrier oscillation at the oscillating stage output is better than 14 dB with respect to the level of required harmonic. This operation mode of the oscillating stage allows to reduce the level of unwanted harmonics and thus improves the jitter performance. The waveform at the collector of the transistor is shown in figure 2.

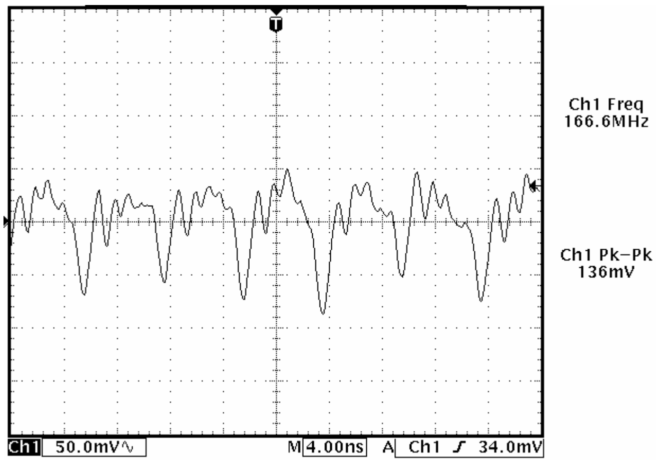


Fig 2 .The waveform in the collector circuit

The waveform in the collector circuit displays that the signal of the chosen harmonics gets an additional energy only once a period of a basic oscillation. So the influence of the chosen harmonics on the basic oscillation is restricted by 1/12th part of a basic oscillation period. The time of large amplitude in the collector circuit corresponds to a positive front of a basic oscillation, thus it accelerates the transistor opening. The influence of the collector voltage on the transistor base enhances an equivalent input admittance of the transistor and enlarges a loaded Q-factor of a quartz resonator.

The second stage of oscillator is a narrow band amplifier, which is also tuned on desired frequency 1 GHz. To provide a stability of a XO operation mode it is necessary to pay attention to isolating oscillator stage from the filtering and amplification stages, and for power-supply decoupling of all the stages. The buffer stage is an ECL differential receiver /driver with Enable/Disable feature.

## IV. Measurement Results

The plots of the single side band phase noise spectral density $L_{\varphi}(f)$ versus frequency offset $f$ are presented on Figure3.

Presented curves show that the loaded Q-factors of a quartz resonator are approximately 16,000 for 1GHz oscillator and 20,000 for 622MHz VCXO. These values approach unloaded Q-factor values for AT-cut inverted mesa crystal resonators at frequencies of 166.67 MHz and 103.7 MHz respectively. The same phase noise level on the floor of power spectral density is due to the same frequency multiplication factor and equal sensitivity of an L-band amplifier.

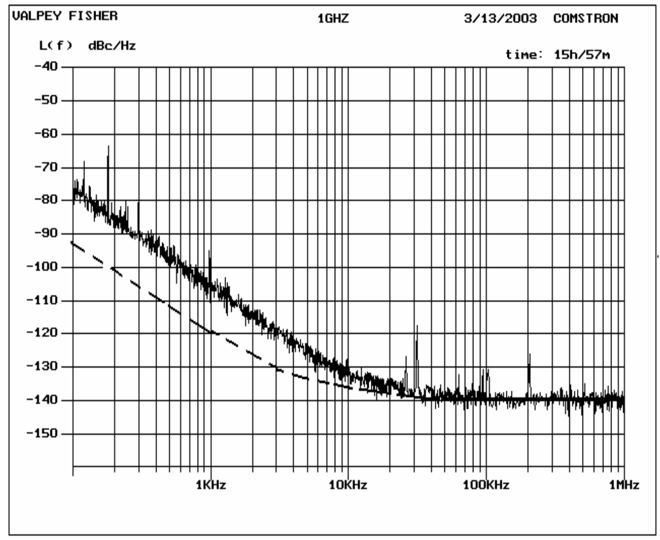


Fig. 3.The single side band phase noise spectral density $L_{\varphi}(f)$ of 1GHz XO and 622MHz VCXO.

The upper curve is for 1GHz crystal oscillator. The frequency multiplication factor is 6 in both cases. The bottom dashed curve is for 622.08 MHz VCXO, which is based on the same technique of the frequency multiplication as described XO.

The plot of frequency stability over temperature of XO is presented in Figure 4.

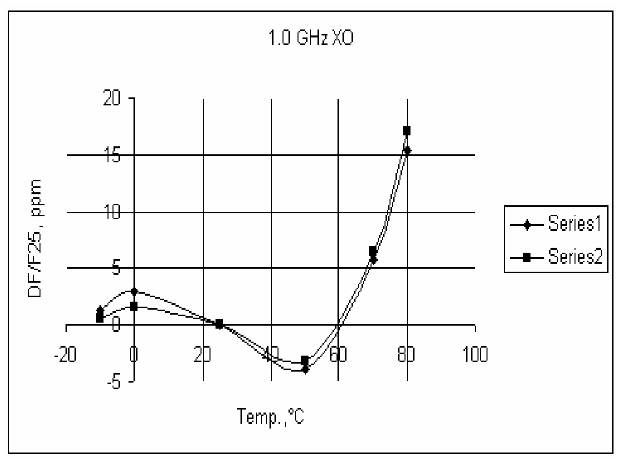


Fig. 4. The dependence of frequency stability $\Delta f/f_0$ over temperature $t$.

This curve is in close agreement with classical definition of the frequency/temperature dependence of the crystal resonators. It indicates that phase shift cased by a presence of the selected harmonic is compensated in wide temperature range. The spectrum of XO output signal is shown in Figure 4.

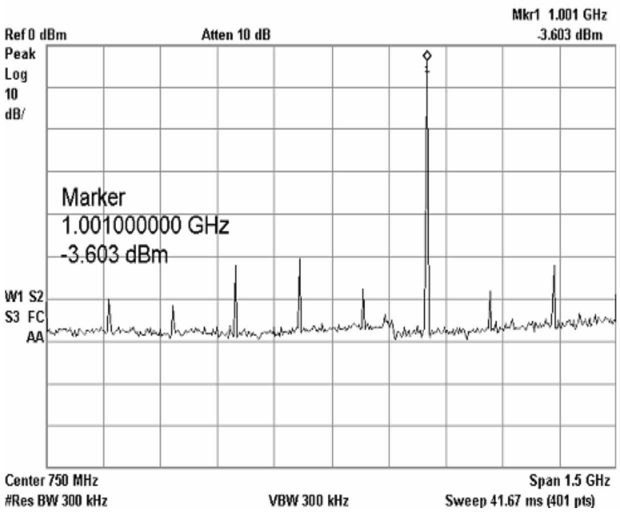

Fig. 4. The spectrum of 1 GHz XO signal.

The suppression of sub-harmonics and their multiples is better than 50 dB with respect to the carrier signal at 1.0 GHz.

## V. CONCLUSIONS

This method of two oscillations "superimpose" has allowed to generate the low noise L-band signals based on AT-cut inverted mesa crystal resonators. The jitter of described XO meets the specification of modern digital communication protocols. It does not exceed 1 ps value in a noise frequency band from 100Hz to 20 MHz. That value is much better than phase jitter achieved by best SAW oscillators in close-to-the-carrier range. In addition XO is capable of providing the best frequency stability over temperature, time, and initial calibration, that does not exceed ±20 ppm overall operating conditions. A positive influence of the selected harmonic on a loaded Q-factor of quartz resonator is the key factor for achieving low phase jitter and for a reduction of inserted "technical" noise.

## REFERENCES

1. M.C. Chow "Understanding SONET/SDH" published by Andan Publisher, 2000
2. M.K. Littman "Building Broadband Networks", CRC Press 2002
3. D.V. Bogomolov, R Boroditsky, E.A. Silaev "Low phase jitter in UHF VCXO" *Proceeding of the* 2002 EFTF.
4. T.E. Parker, G.K. Montress , "Spectral purity of acoustic resonator oscillators". *Proc. of the* 1992 IEEE *int. Freq. Contr. Symp.*, 340-348.
5. S.J. Goldman, "Phase Noise Analysis in Radar Systems", Using Personal Computers, JOHN WILEY and SONS, 1989.
6. D.A. Howe, D.W. Allan and J.A. Barnes, "Properties of Signal Sources and Measurement Methods ", *Proc. 35th Annu.*., pp. 1-47, May 1981.
7. D.V. Bogomolov "Phase Jitter Minimization In UHF Band VCXO" *Proc. of the* 2002 IEEE *Int. Freq. Contrl. Symp. P p619-621*