LOW PHASE NOISE KU BAND PUSH – PUSH OSCILLATOR

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Abstract

As commonly known, oscillators play very important role in all communication and test equipment. Most of modern communication systems are using different types of digital modulation techniques. That's why Bit Error Rate is key parameter, used to evaluate quality of communication equipment. Improving of this parameter is related to using oscillators with low phase noise in transmitters and receivers. Design of low noise oscillators become a major task for engineers. With increasing frequency of generated signal this task is hardly desirable. In this paper is presented method for solving this problem. A Clapp Voltage Controlled Oscillator in push – push configuration using SiGe bipolar junction transistor is presented. The oscillator is used in Ku band and reaches phase noise performance down to -100dBc/Hz at 100 KHz offset and tuning range of 10%.

1. Introduction

The push – push principle is widely accepted as approach to realize low phase noise high frequency oscillators. To be reached good phase noise performance of oscillators is necessary to be used resonators with high Q factor. In microwave frequencies are widely used dielectric resonators. Oscillators realized with them have very good phase noise but are difficult for implementation. Oscillation frequency should be tuned manually using screw. Furthermore frequency stability over temperature changing is not sufficient for bulk of modern communication equipment. Decision of this problem is to be used frequency synthesizers. This leads to need of high frequency voltage controlled oscillators. For their realization are used varactor diodes as tuning elements. At high frequencies (X, KU, Ka band) varactor diodes have low Q factor. This is the main difficulty in design low phase noise VCO's. Furthermore they have parasitic resonances, which sometimes make design of such oscillators impossible. These problems can be solved using push - push oscillator. The idea is to be designed two oscillators working at half of desired output frequency. After coupling them the output spectrum contain only even harmonics. Second harmonic can be used as output frequency.

2. Push – push oscillators

Simplified schematic of two coupled oscillators is shown in fig.1. Considering the transmission line acts as resonant circuit in addition to coupling network, and for simplification in the analysis, the loss associated with the transmission line is assumed as part of load admittances G_L. In fig.1 Y_{d1} and Y_{d2} represent equivalent admittance of two active devices and their loads, while Y_{C1} and Y_{C2} represent admittances seen by devices in mutually coupled oscillator circuit.

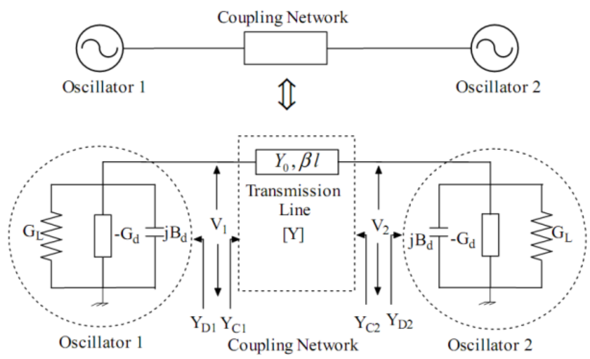

Fig. 1. Principle schematic of coupled oscillators

For coupling two oscillators phases of output signals must be synchronized. Phase synchronization is reached with transmission line with characteristic admittance Y0 and electrical length βl. The electrical length of transmission line has to be chosen such that both oscillators are working individually and generate the same output frequency. For this reason active devices have to see the same impedance from the both sides of transmission line. This can be realized if electrical length is chosen to be half wavelength for fundamental frequency of oscillators. Figure 2 shows the push – push oscillator using half – wavelength microstrip resonator. For fundamental frequency f0 this resonator has a null point at the centre of microstrip line, being a point of oscillator symmetry which is considered as virtual ground or short – circuited point. In this case, the resonance voltage has maximum values at both ends of resonator with phase difference of 180deg and resonance voltage is zero at the centre of resonator. For desired second harmonic frequency 2f0 such point could be regarded as an open circuited point.

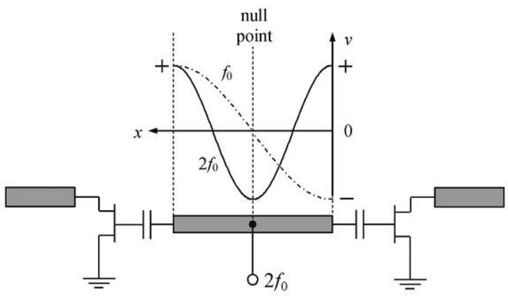

Fig. 2. Push – push microstrip oscillator configuration

For analysis purpose, transmission line is characterized as two port network with its terminal voltages represented by voltage phasor as $V_1 = |V_1| e^{j\varphi_1}$ and $V_2 = |V_2| e^{j\varphi_2}$ where $|V_1|$, $|V_2|$, φ1 and φ2 are magnitudes and phases of voltage phasors. Transmission line can be represented with its ABCD matrix:

$$(2.1)\quad ABCD = \begin{bmatrix} \cos\beta l & jZ_0 \sin\beta l \\ jZ_0 \sin\beta l & \cos\beta l \end{bmatrix},$$

where Z_0, l and β are characteristic impedance, length and phase constant of transmission line. For purpose of this analysis is necessary to be calculated Y matrix of transmission line. Relationship between Y matrix and ABCD matrix is:

$$(2.2)\quad Y_{11} = \frac{D}{B};\quad Y_{12} = \frac{BC - AD}{B};$$

$$Y_{21} = -\frac{1}{B};\quad Y_{22} = \frac{A}{B}$$

From 2.1 and 2.2 Y matrix is given by:

$$(2.3)\quad Y_{TRL} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} =$$

$$= \begin{bmatrix} -jY_o \cot\beta l & jY_0 \dfrac{1}{\sin\beta l} \\ jY_0 \dfrac{1}{\sin\beta l} & -jY_o \cot\beta l \end{bmatrix}$$

The circuit equation for Fig.1 at transmission line terminals can be expressed as

$$(2.4)\quad -Y_{D1}|V_1|e^{j\phi_1} = Y_{11}|V_1|e^{j\phi_1} + Y_{21}|V_2|e^{j\phi_2}$$

$$(2.5)\quad -Y_{D2}|V_2|e^{j\phi_2} = Y_{21}|V_1|e^{j\phi_1} + Y_{22}|V_2|e^{j\phi_2}$$

Equations 2.4 and 2.5 can be expressed in matrix form as:

$$(2.6)\quad \begin{bmatrix} -Y_{D1}V_1 \\ -Y_{D1}V_1 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}$$

For identical coupled oscillators:

$$(2.7)\quad V_1 = V_2 = V;\ Y_{D1} = Y_{D2} = Y_D;\ Y_{c1} = Y_{c2} = Y_c$$

From equations 2.4, 2.5 and 2.7

$$(2.8)\quad e^{\pm j(\varphi_1 - \varphi_2)} = e^{\pm j(\Delta\varphi)} = \frac{Y_D + Y_{11}}{-Y_{12}}$$

The admittance Y_D comprises of device admittance and load conductance as

$$(2.9)\quad Y_D = G_L - G_D + jB_D$$

The admittance Y_C is given from the transmission line equation as

$$(2.10)\quad Y_C = Y_0 \left[\frac{Y_D + jY_0 \tan(\beta l)}{Y_0 + jY_D \tan(\beta l)} \right] =$$

$$= Y_0 \left[\frac{Y_D + jY_0 \tan\Theta}{Y_0 + jY_D \tan\Theta} \right]$$

To be satisfied conditions for oscillation, the length of transmission line is selected such that real and imaginary part of admittance Y_C is given by:

$$(2.11)\quad \mathrm{Re}[Y_C] = G_L - G_D$$

$$(2.12)\quad \mathrm{Im}[Y_C] = -jB$$

From equations 2.9 and 2.10

$$(2.13)\quad \tan(\beta l) = \frac{2B_D Y_0}{{B_D}^2 - {Y_0}^2 + (G_L - G_D)^2}$$

During the process of starting up oscillations, the real part of admittance Y_D is more negative then admittance of losses. As level of generated signal increases, the device gain drops until the losses are compensated. Under the steady state oscillation conditions, G_L-G_D=0 and electrical length Θ of transmission line is given from equation 2.13 as

$$(2.14)\quad \tan(\beta l)=\frac{2B_DY_0}{B_D^{\,2}-Y_0^{\,2}}\Leftrightarrow$$

$$\Theta=\beta l=\tan^{-1}\left[\frac{2B_DY_o}{B_D^{\,2}-Y_0^{\,2}}\right]$$

To be determined Y matrix of transmission line is necessary to be defined *cot(βl)* and *cosec(βl)* functions.

$$(2.15)\quad \cot(\beta l)=\tan^{-1}(\beta l)=\frac{B_D^{\,2}-Y_0^{\,2}}{2B_DY_0}$$

$$(2.16)\quad \frac{\cos(\beta l)}{\sin(\beta l)}=\frac{B_D^{\,2}-Y_0^{\,2}}{2B_DY_0}\Leftrightarrow\frac{1-\sin^2(\beta l)}{\sin^2(\beta l)}=$$

$$=\frac{B_D^{\,4}-2B_D^{\,2}Y_0^{\,2}+Y_0^{\,4}}{4B_D^{\,2}Y_o^{\,2}}\Leftrightarrow$$

$$\Leftrightarrow \cos ec(\beta l)=\frac{1}{\sin(\beta l)}=\frac{B_D^{\,2}+Y_0^{\,2}}{2B_DY_0}$$

The [Y] parameter of the transmission line can be rewritten from equations 2.3, 2.15 and 2.16 as

$$(2.17)\quad Y_{TRL}=\begin{bmatrix}Y_{11} & Y_{12}\\ Y_{21} & Y_{22}\end{bmatrix}=$$

$$=\begin{bmatrix}-j\dfrac{B_D^{\,2}-Y_0^{\,2}}{2B_D} & j\dfrac{B_D^{\,2}+Y_0^{\,2}}{2B_D}\\ j\dfrac{B_D^{\,2}+Y_0^{\,2}}{2B_D} & -j\dfrac{B_D^{\,2}-Y_0^{\,2}}{2B_D}\end{bmatrix}$$

Phase difference between generated signals from two coupled oscillators can be determined from equations 2.8 and 2.17 and is given as

$$(2.18)\quad e^{\pm j(\varphi_1-\varphi_2)}=e^{\pm j(\Delta\varphi)}=\frac{Y_D+Y_{11}}{-Y_{12}}=\left[\frac{Y_D-j\dfrac{B_D^{\,2}-Y_0^{\,2}}{2B_D}}{-j\dfrac{B_D^{\,2}+Y_0^{\,2}}{2B_D}}\right]$$

In steady state oscillator mode $Y_D = jB_D$

$$(2.19)\quad e^{\pm j(\Delta\varphi)}=\left[\frac{\dfrac{2jB_D^{\,2}-jB_D^{\,2}+Y_0^{\,2}}{2B_D}}{-j\dfrac{B_D^{\,2}+Y_0^{\,2}}{2B_D}}\right]=-1$$

$$(2.20)\quad e^{\pm j(\Delta\varphi)}=-1\Rightarrow\Delta\varphi=\varphi_1-\varphi_2=\pm180^\circ$$

With equations 2.1 – 2.20 was mathematically proven that two coupled oscillators generate phase synchronized signals with the same frequency and phase difference 180. If these two signals are summed in phase, with appropriate power combiner, the output signal in summing port can be expressed as

$$(2.23)\quad V_{out}(t)=V_{out\_1}(t)+V_{out\_2}(t)=$$

$$=\sum_n A_n e^{jn(\omega_0 t)}+\sum_n A_n e^{jn(\omega_0(t-\Delta t))}$$

Where **n** is harmonic number.

Equation 2.23 can be rewritten as

$$(2.24)\quad V_{out}(t)=A_1e^{j\omega_0 t}\left(1+e^{j\omega_0\Delta t}\right)+$$

$$A_2e^{j2\omega_0 t}\left(1+e^{j2\omega_0\Delta t}\right)+A_3e^{j3\omega_0 t}\left(1+e^{j3\omega_0\Delta t}\right)+\ldots$$

From equation 2.20, generated signals have phase difference 180 so $\omega_0\,\Delta t=\pi$

$$(2.25)\quad e^{-j\pi}=\cos(-\pi)+j\sin(-\pi)=-1$$

$$(2.26)\quad e^{-j2\pi}=\cos(-2\pi)+j\sin(-2\pi)=1$$

From 2.24, 2.25 and 2.26 the output signal of push – push oscillator is determined as

$$(2.27)\quad V_{out}(t)_{push-push}=\sum_n^2 2A_2e^{j2\omega_0 t}+$$

$$+2A_4e^{j4\omega_0 t}+2A_6e^{j6\omega_0 t}+\ldots.$$

Equation 2.27 shows cancellation of all odd harmonics especially the fundamental signal, where odd harmonics are added constructively. The higher order harmonics (4ω, 6ω, 8ω are filtered out).

3. Applications of push – push concept

In general push – push concept offers several advantages over single ended design:

- Since the transistors are operated at half of desired output frequency, the usable frequency range of devices can be extended;
- Simultaneous generation of both fundamental and second harmonic is feasible. Feeding f_0 into a frequency divider instead of $2f_0$ lowers divider efforts.
- Phase noise is reduced because of synchronization effects.
- High immunity against load pull.
- Extension of tinning range.

4. Design push-push VCO

The fowling shows example for design of mutually synchronized coupled voltage controlled oscillators. Generated signal can be tuned in range from 10.4GHz to 11.4GHz ($2f_0$) in which two individual oscillators oscillates at range of 5.2GHz to 5.7GHz. Figure 3 shows the circuit diagram of push – push oscillator. The circuit is fabricated on 0.51mm Rogers substrate of dielectric constant 3.38 and loss tangent $2.7.10^{-4}$. Active devices, used to generate negative resistance are SiGe BJT transistors BFP620, produced by Infineon. As tuning elements are used varactor diodes BB837 also produced by Infineon.

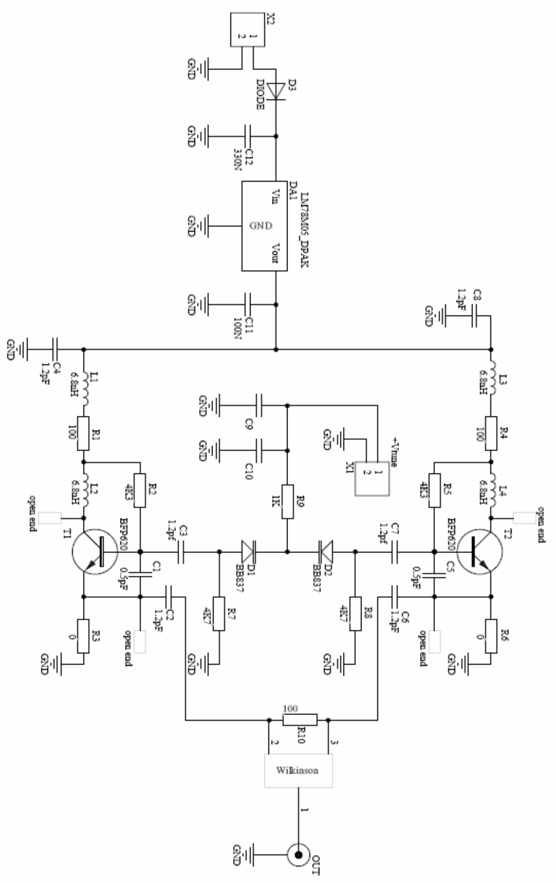

Fig. 3. Circuit diagram of push-push VCO

Figure 4 shows simulated (Ansoft Designer) base currents Ib_1 and Ib_2 which are phase shifted at 180 degree in mutually synchronized condition.

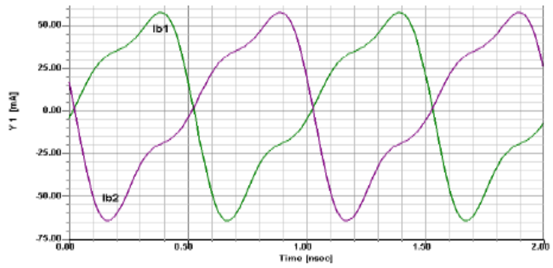

Fig. 4. Base currents of both transistors in push-push oscillator

The PCB layout of push – push oscillator is shown in fig.5. Outputs from both oscillators are summed by using Wilkinson combiner, designed for $2f_0$ frequency.

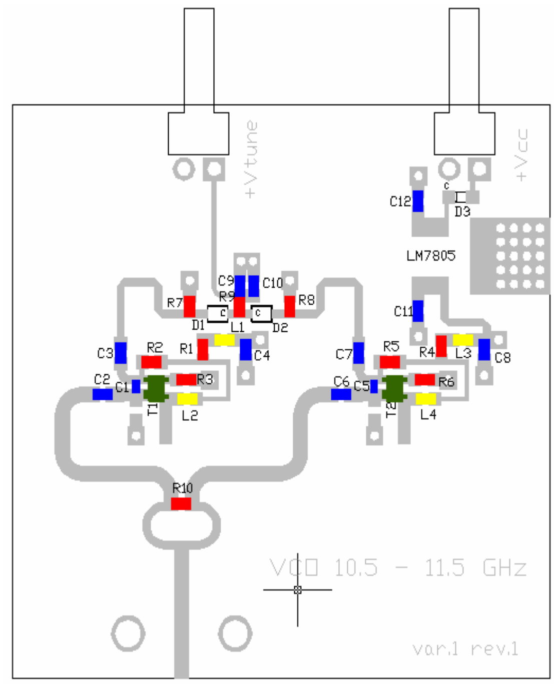

Fig. 5. PCB layout of push – push VCO

Measured results of oscillator parameters are presented graphically in figures 6, 7 and 8. Output spectrum is shown in fig.6. Suppression of first harmonic is about 25dB below second harmonic. This is due to non-ideal symmetry of the circuit. Two transistors with absolutely the same parameters are almost impossible to be found. First harmonic suppression can be improved by using active biasing of transistors.

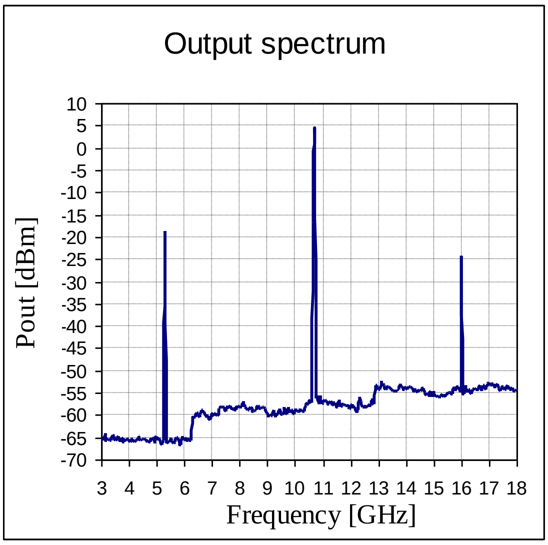

Fig. 6. Measured output spectrum of push – push oscillator

Figure 7 shows measured tuning range of designed voltage controlled oscillator.

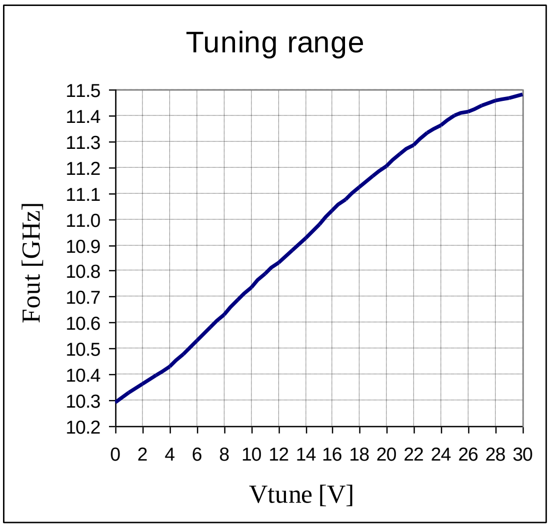

Fig. 7. Measured tuning range of designed VCO

Results from phase noise measurement at second harmonic of push – push oscillator are depicted in Fig.8. Measurements were performed for shorted tuning input and with 9V tuning voltage applied on it. It can be seen that, with shorted tinning input is retched about 3dB better phase noise than with applied 9V tuning voltage. This can be explained with noise added from voltage souse at input of VCO.

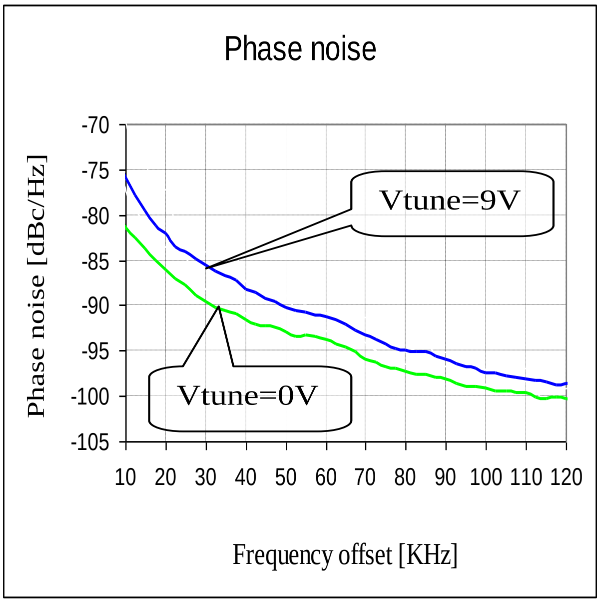

Fig. 8. Measured phase noise at second harmonic of push-push VCO

5. Conclusion

The main goal of this paper is to present method for design microwave voltage controlled oscillators with low phase noise. It was analytically shown that is possible to synchronize two oscillators and frequency of generated signal to be twice fundamental frequency of single oscillator. This statement is very important in design microwave VCO's, because it is general method for reducing phase noise. A example for Ku band VCO design, using mutually coupled oscillators was presented. Measurement results of manufactured VCO confirm statement that two oscillators can be synchronized to generate twice bigger output frequency.

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