Circuit Architectures for Low-Phase-Noise Oscillators

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In this paper some considerations on different oscillator topologies are presented with the aim of analyzing their behavior in terms of phase noise performance. In particular, our analysis suggests that a 9db improvement in the phase noise level can be obtained when using a "Push-Push" oscillator architecture in comparison with a fundamental-frequency oscillator developed under the same conditions. Simulations of different oscillator topologies, which confirm the proposed theory, are shown in the paper.

INTRODUCTION

In communications systems, oscillators define the reference for signal transmission and reception. The active device low frequency (LF) noise (mainly flicker noise), which is up-converted in oscillator frequency and phase noise (PN), sets the ultimate system performance. For these reasons, oscillators must exhibit the lowest phase noise they can. The phase noise level depends on the application and is strongly influenced by the operating frequencies, the active device technology, the passive components and resonator quality factor Q. Usually, the lower is the oscillator frequency, the higher is the quality factor of the resonator and other passive components.

Once the oscillating frequency is given, the fundamental choices in order to obtain the minimum phase noise are:

1. a resonator with a high unloaded Q;
2. a technology with low active-device flicker noise and high-Q passive components;
3. a circuit design which exploits the above items and minimizes the conversion factor between the LF noise and the oscillator phase noise.

In this paper some advantages of the *"Push-Push"* (PP) oscillator topology in terms of phase noise properties are put in evidence and preliminarily verified by means of a simple theoretical analysis and simulation results. In particular, for the first time to our knowledge and in agreement with some experimental results [6,7], a 9dB PN improvement for the PP oscillator topology, with respect to a conventional oscillator operating at the same frequency, is theoretically justified.

OSCILLATOR TOPOLOGIES

To realize a microwave oscillator at a frequency f_0 one of the following approaches can be adopted [1]:

(a) *"Fundamental-frequency oscillator"* at f_0: this is the simplest configuration, but its performance can be strongly limited by device technology at high frequencies (e.g., low gain and power, poor flicker-noise characteristics, etc..). Moreover, the possibly low quality factor of resonators at high frequencies, may furthermore limit the phase noise performance.

(b) *"Oscillator with frequency doubler"*: this configuration is often used to mitigate some of the problems mentioned in (a): a fundamental-frequency oscillator operating at half the desired frequency ($f_0/2$) is cascaded with a frequency multiplier circuit for generating the desired tone. This approach can usually relay on the availability of active devices having better characteristics (gain, power, flicker noise, etc..) due to the reduced operating frequency $f_0/2$ of the oscillator. In addition, a higher Q-resonator can be employed which improves both phase noise and oscillator stability. One of the main drawback of this approach is the increased complexity due to presence of additional components, besides the frequency doubler.

(c) *"Push-push oscillator":* this is an interesting approach which has the advantage of the oscillators operating at half the desired frequency (better active device performance and resonator Q), but allows for a more compact implementation avoiding the additional post multiplication, filtering and amplification stages required for the frequency-doubler configuration. The PP topology, in its more typical application, consists of two identical, mutually synchronized fundamental-frequency oscillators operating at half the desired output frequency ($f_0/2$) which drive a common resonator with signals that are 180° out of phase each other. The phase coupling network and the output one are designed in such a way that the fundamental harmonics add out of phase, while the second harmonics add in phase, achieving the oscillation at the wished frequency f_0. This configuration, in spite of a little circuital complication, can really offer advantages, compared to other approaches; for instance the possibility to achieve operating frequencies beyond the limitation due to the cut-off frequency of available technology and the capability of providing both $f_0/2$ and f_0 frequencies [2]. In addition to such characteristics, PP oscillators can exhibit excellent PN improvement with respect to other architectures even when considering the same resonator quality factor and active device flicker-noise performance. In particular, in the next sections it is shown that, theoretically, a phase noise improvement of 9dB with respect to the fundamental-frequency topology (a) and 3dB with respect to the frequency-doubler one (b) is obtained.

OSCILLATOR PHASE NOISE ANALYSIS

The phase noise analysis, which is adopted in the paper to make a comparison between the three different oscillator topologies, is based on the *"pushing factor"* (*PF*) [3,4].

In this kind of analysis, the effect of the active device low frequency noise on the oscillation is evaluated by considering the frequency sensitivity to a small-signal DC voltage perturbation, under the usually justified hypothesis of steady-state behavior of the circuit with respect to the LF noise bandwidth. More precisely, by assuming a dominant noise source, the *PF* is evaluated by applying a DC small signal voltage perturbation ΔV to the base-emitter junction in bipolar transistors or to the gate-source junction in MOS and MESFETs [4]:

$$PF = \frac{\Delta f_0}{\Delta V} \quad \text{[Hz/V]} \qquad (1)$$

It can be shown [3] that, under the above assumptions, the single-side-band phase noise is directly related to the pushing factor PF by:

$$\ell(f_m) = 20\log\left(\frac{\Delta f}{\sqrt{2}\cdot f_m}\right) = 20\log\left(\frac{PF\Delta\tilde{v}}{\sqrt{2}\cdot f_m}\right) \quad \text{[dBc/Hz]} \qquad (2)$$

where Δf is the oscillator frequency noise (square root of frequency noise spectral density [Hz^2/Hz]), f_m the offset frequency from the carrier and $\Delta\tilde{v}$ the input noise voltage $(V/\sqrt{Hz})$.

In order to compare different oscillator topologies, the *PF* is first of all evaluated for a fundamental-frequency oscillator at $f_0/2$, as a function of the main parameters related to a classical, negative-resistance oscillator described by the simplified scheme in Fig.1. In particular, this model describes the oscillator as a parallel resonator R_r , L_r , C_r connected to an active dipole represented in terms of a negative conductance and capacitance nonlinearly dependent on the oscillator amplitude V_{OSC}.

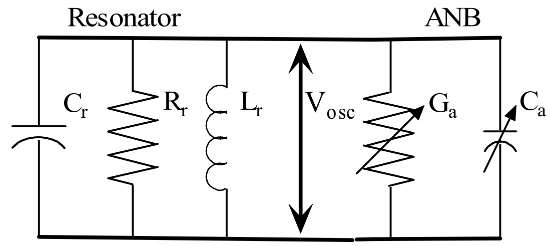

Fig.1: Simplified oscillator model

By using this model, it is quite clear to see that the variation of the capacitance C_a due to the LF noise gives rise to a frequency/phase deviation of the oscillation. In particular, it is possible to write the pushing factor as:

$$PF_{|f_0} = \frac{1}{2\pi}\frac{\Delta\omega_0}{\Delta V} = \frac{1}{2\pi}\frac{\partial\omega_0}{\partial C_a}\frac{\partial C_a}{\partial V} \qquad (3)$$

The first derivative in (3) can be written as:

$$\frac{\partial\omega_0}{\partial C_a} = \frac{\omega_0\omega_{res}R_r}{2(Q+\omega_{res}R_rC_a)} \qquad (4)$$

where $\omega_{res} = \sqrt{1/L_rC_r}$ and ω_0 are the resonator and oscillator angular frequencies, respectively. From (3) and (4) it is possible to write:

$$PF_{|f_0} = \frac{1}{2\pi}\cdot\frac{\omega_0\omega_{res}R_r}{2(Q+\omega_{res}R_rC_a)}\cdot\frac{\partial C_a}{\partial V} \qquad (5)$$

Moreover, it is straightforward to compute the *PF* for an oscillator at $f_0/2$ having the same quality factor Q:

$$PF_{|\frac{f_0}{2}} = \frac{1}{2\pi}\cdot\frac{\omega_0\omega_{res}R_r}{4\cdot(2\cdot Q+\omega_{res}R_rC_a)}\cdot\frac{\partial C_a}{\partial V} \qquad (6)$$

Since $\frac{\partial C_a}{\partial V}$ can be assumed to be independent from the working frequency, the ratio between the two *PF*'s can be finally written as:

$$\frac{PF_{|f_0}}{PF_{|\frac{f_0}{2}}} = 4 \qquad (7)$$

This ratio (which, using (2), gives a 12dB/octave PN worsening) is calculated in the particular case of $\omega_0 = \omega_{res}$. This condition occurs when the resonator has a very high quality factor or in a well-designed oscillator where the imaginary parts of the active device admittance is negligible with respect to the resonator susceptance (i.e., $C_a \approx 0$ in Fig.1) in order to preserve the frequency stabilization properties of the resonator [8]. Clearly, the 12dB/octave phase noise worsening evaluated above is based on a simplified model; however it should also be considered that, in practical conditions, this figure could be even larger, since both the resonator and the LF noise characteristics of the required active device become reasonably worse when the operating frequency is doubled.

As far as the frequency doubler architecture (b) is concerned, it is well known [3], that for every ideal ×2 multiplication of the signal, the phase noise gets 6dB worse, so this is the ultimate performance when using a frequency multiplier.

Let us now consider the push-push circuit behavior. The pushing factor evaluation in this circuit can be carried out by considering two different, uncorrelated perturbations ΔV_1 and ΔV_2 associated to the transistors. Moreover, thanks to the symmetry of the circuit, it is convenient to study the problem in terms of common (CM) and differential mode (DM) perturbations. A CM pushing factor PF_{CM} and a DM one PF_{DM} are calculated applying respectively a CM perturbation ($\Delta V_1=\Delta V_2=\Delta V/2$) and a DM one ($\Delta V_1=-\Delta V_2=\Delta V/2$).

On this basis, the frequency noise spectral density can be written as:

$$\begin{aligned}\left\langle \Delta f_{PP}^2 \right\rangle &= \left\langle \left(\Delta f_{CM} + \Delta f_{DM}\right)^2 \right\rangle = \\ &= PF_{CM}^2 \left\langle \Delta\tilde{v}_{CM}^2 \right\rangle + PF_{DM}^2 \left\langle \Delta\tilde{v}_{DM}^2 \right\rangle + \\ &\quad + 2 \cdot PF_{DM} \cdot PF_{CM} \left\langle \Delta\tilde{v}_{DM} \cdot \Delta\tilde{v}_{CM} \right\rangle\end{aligned} \tag{8}$$

However, the differential perturbation, due to system symmetry, gives no variation of the oscillating frequency (i.e., $PF_{DM} = 0$). This quite obvious result has been verified also by means of frequency sensitivity simulations carried out on a push-push oscillator design.

The common mode input noise voltage of the transistors can be written as:

$$\begin{aligned}\left\langle \Delta\tilde{v}_{CM}^2 \right\rangle &= \left\langle \left(\frac{\Delta\tilde{v}_1 + \Delta\tilde{v}_2}{2}\right)^2 \right\rangle = \\ &= \frac{1}{4}\left[\left\langle \Delta\tilde{v}_1^2 \right\rangle + \left\langle \Delta\tilde{v}_2^2 \right\rangle + 2\left\langle \Delta\tilde{v}_1 \cdot \Delta\tilde{v}_2 \right\rangle\right]\end{aligned} \tag{9}$$

where $\Delta\tilde{v}_i$ (i=1,2) are the input noise voltages in the two devices, uncorrelated each other (i.e., $<\Delta\tilde{v}_1 \cdot \Delta\tilde{v}_2>=0$). Since the two transistors are identical and work under the same conditions, their input noise voltages are described by the same statistic, that is $\left\langle \Delta\tilde{v}_1^2 \right\rangle = \left\langle \Delta\tilde{v}_2^2 \right\rangle$ and (9) becomes:

$$\left\langle \Delta\tilde{v}_{CM}^2 \right\rangle = \frac{\left\langle \Delta\tilde{v}_1^2 \right\rangle}{2} \tag{10}$$

On this basis, and taking in account that $PF_{DM} = 0$, from (8) and (10) the frequency noise spectral density of the push-push oscillator is simply:

$$\left\langle \Delta f_{PP}^2 \right\rangle = PF_{CM}^2 \frac{\left\langle \Delta\tilde{v}_1^2 \right\rangle}{2} \tag{11}$$

Finally, substituting (11) in (2) it is possible to compare the phase noise level in the push-push and in the “half-frequency oscillator” composing the PP circuit. We found a 3dB PN improvement, coherently with the analysis provided in [5]. This 3dB improvement is computed for the fundamental harmonic $f_0/2$. By considering that the desired output frequency is at the second harmonic, the phase noise around f_0 is 6dB worse. In conclusion, it results that when using a push-push oscillator to synthesize a signal reference at f_0, the phase noise gets only 3dB worse with respect to a single oscillator designed at $f_0/2$. This gives exactly a 9dB improvement compared with the fundamental-frequency solution adopted (which has a 12dB worsening with respect to an $f_0/2$ oscillator) and is coherent with experimental data provided in some papers [6,7] without a clear justification.

VALIDATION

The validation of the above theoretical results was carried out by means of transistor-level simulations of a push-push VCO in the Agilent ADS 2001 environment. Figure 2 shows the schematic of the oscillator circuit adopted. The two “half-frequency oscillators” composing the PP circuit oscillate at $f_0/2$ = 1GHz, while the push-push topology is designed to suppress the first harmonics and sum the second harmonics of the two sub-circuits in phase, at 2GHz. As in the proposed demonstration, the phase noise around 2GHz of the push-push was found to be exactly 3dB worse than the phase noise around 1GHz of the single half oscillator, as shown in Fig.3.

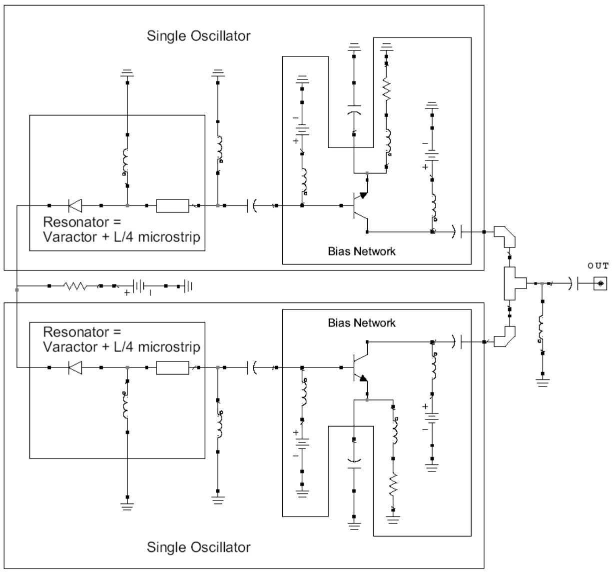

Fig.2: Schematic of the push-push oscillator used in the simulations.

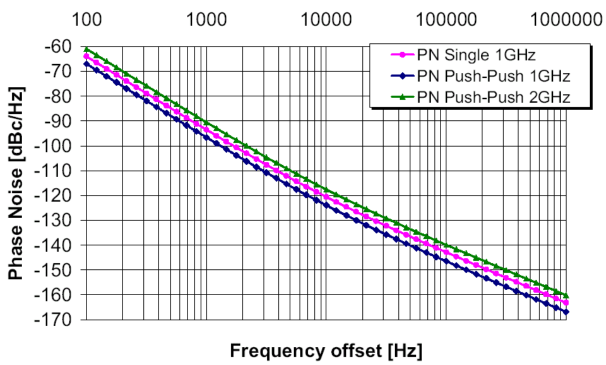

Fig.3: Phase Noise simulations for the 'half oscillator' (at 1GHz) and the push-push oscillator at 1 and 2 GHz.

The "half-oscillator" composing the push-push circuit was then used as the starting point to verify the 12dB/octave PN worsening theoretically predicted in the previous section for the fundamental-frequency oscillator. Unfortunately, it is not an easy task to design two oscillators, operating at $f_0/2$ and f_0, maintaining unchanged parameters as the transistor working point, output power, resonator coupling and quality factor, matching impedance and so on. To overcome this problem, the analysis was carried, on the same circuit design, in an incremental way around the $f_0/2$ oscillator frequency. Simulation results provided a 12dB/octave phase noise worsening as theoretically predicted.

CONCLUSIONS

Push-push oscillators are used for their advantages at radio, micro- and millimeter-wave frequencies. In the paper, for the first time to our knowledge, it is explained, on the basis of simple models and noise analysis techniques, that a theoretical improvement of 9dB in phase noise performance can be obtained with respect to fundamental-frequency oscillators. Accurate circuit simulations confirm the theoretical results.

A hybrid push-push oscillator is being manufactured by SIAE Microelettronica (Fig.4) and noise measurements will be performed to have also an experimental validation of the proposed theory.

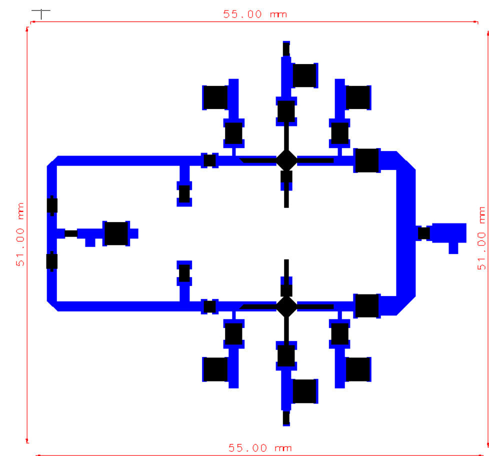

Fig.4. Layout of the hybrid Push-Push oscillator.

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