Nonlinear simulation techniques for the optimized design of push-push oscillators

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Abstract — **In the push-push oscillator, the circuit symmetry enables, through a suitable choice of terminating impedances, an output frequency that is twice the oscillation fundamental frequency. The main difficulty is the complexity of the design, for which there is a lack of specific simulation tools. Here, a harmonic-balance technique is presented, allowing the circuit optimization for prefixed oscillation frequency and maximum output power at the second harmonic component. The oscillator dynamics is analyzed through the envelope transient approach, making use of a new initialization technique of the circuit variables. For a realistic prediction of the first-harmonic cancellation, a sensitivity analysis is performed. A continuation technique is applied to obtain the variation of the output power and frequency versus inequalities in significant circuit parameters. The circuit phase noise is analyzed through the envelope transient approach. The techniques have been applied to a 18 GHz push-push oscillator, with very good agreement with the experimental results.**

I. INTRODUCTION

In the push-push configuration the oscillator power is extracted at twice the fundamental frequency [1]. The generation of a strong second harmonic in the individual oscillators is required, together with the cancellation of the oscillation first harmonic component at the circuit output. This is achieved through a suitable choice of the terminating impedances, providing a 180° phase shift of the odd harmonic components (odd-mode oscillation). The advantages of the push-push configuration are the increase of the frequency generation capabilities of the transistor and the reduction of phase noise in comparison with a single oscillator [1-2].

The main difficulty with the push-push oscillator is the complicated design. Obtaining the specified oscillation frequency and output power usually requires a long trial and error process and the designer has to verify the odd-mode oscillation of the circuit. On the other hand, the ideal cancellation of the odd harmonics requires perfect symmetry of the two individual oscillators, which is impossible in practice due to inequalities between the circuit element values and between the transistors. If there is high sensitivity to these inequalities, the actual circuit behaviour can be very different from the expected one.

This work proposes specific tools for the optimized design of push-push oscillators. The aim is to achieve control over the self-oscillation, the second harmonic generation and the cancellation of the fundamental frequency. Parametric analyses, versus the oscillator inequalities are performed, which would prevent an unrealistic design with poor first harmonic cancellation or even a non-synchronized behaviour [3,4]. The analysis of the oscillator, through the envelope transient approach [5,6], with a new initialization technique of the circuit variables is presented and has been employed for the determination of the output phase noise. The tools have been applied to a push-push oscillator with 18 GHz output frequency, obtaining very good agreement in the comparison with measurements.

II. HARMONIC-BALANCE DESIGN

When working in the push-push configuration, the collector currents of the two individual oscillators must have equal amplitude and opposite phase at the first harmonic component (ω_0) and equal amplitude and phase at the second one ($2\omega_0$). This is achieved through the connection of a microstrip coupler between the two base terminals[2]. Although the oscillators are individually analyzed in a first design stage, the variation in the terminating impedances in the push-push configuration influences the behavior; so, the non-linear simulation of the complete circuit will generally be required.

Here, an auxiliary generator (AG) technique [3] is proposed for the design. Two AGs at the oscillation frequency ($\omega_{AG}=\omega_0$) are connected at two symmetric nodes of the circuit (see Fig. 1). The AGs have equal amplitude V_{AG} and a 180° phase shift that ensures the odd-mode oscillation, avoiding the need of verification by the designer. The AGs must fulfil a non-perturbation condition [3] is given by the zero value of the admittance function (AG current-to-voltage relationship). If the oscillation frequency and amplitude are prefixed, at

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$\omega_{AG}=\omega_0$ and $V_{AG}=V_o$, only two circuit variables (identical in the two oscillators) have to be optimized or calculated to simultaneously fulfil the non-perturbation condition in the two AGs.

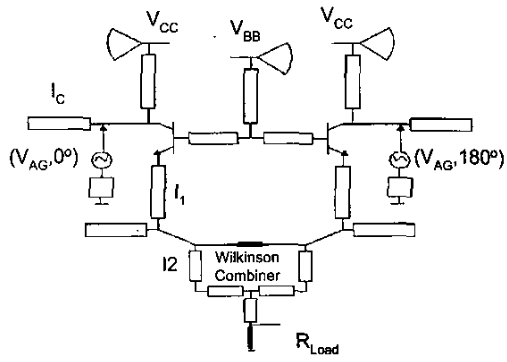


Fig. 1. Circuit schematic with the two AGs for oscillator design

In the design technique, a sweep is performed in V_{AG}, evaluating the output power at the second-harmonic component $2\omega_o$ (see Fig. 2). The frequency keeps constant during the entire amplitude sweep and each point of the sweep corresponds to a different design. In this way, optimum values are obtained for maximum output power at $2\omega_o$. The stability of the selected design must be verified, together with the oscillation start-up conditions. It is important to note that, in case of using only one AG, convergence to the undesired even-mode oscillation would be possible. This is why two AGs are necessary.

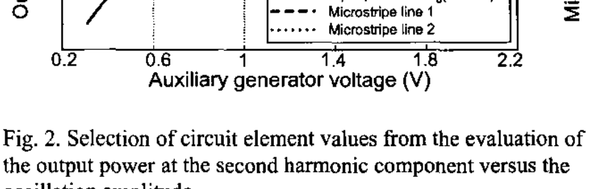


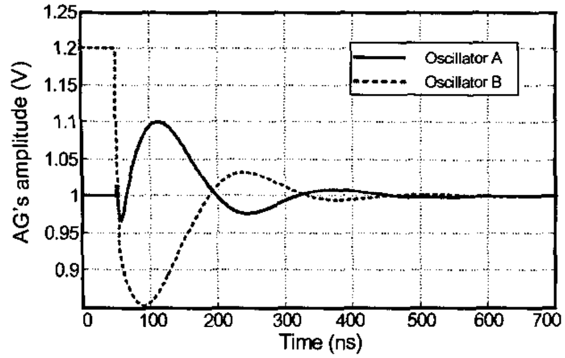
Fig. 2. Selection of circuit element values from the evaluation of the output power at the second harmonic component versus the oscillation amplitude.

III. Envelope Transient Analysis Of The Push-Push Oscillator

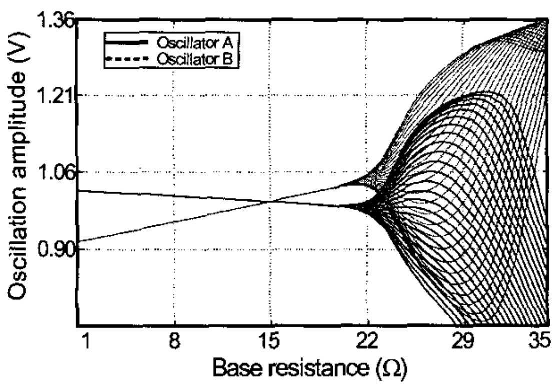
In the envelope transient approach, the circuit variables are expressed in a Fourier series with time-varying phasors of limited bandwidth [5-6]. The technique, due to the time-domain dependence, of the phasors, has great flexibility and is well suited for the analysis of the oscillator dynamics. However it requires a proper initialization of the circuit variables, to avoid trivial solutions, due to the difficulties in the estimation of the fundamental frequency of the series and the sampling rate of the phasors. An efficient initialization technique is proposed here, based on the connection of an AG, at the circuit node N, for a short time interval [0,T]. The AG frequency is ω_{AG} and its constant amplitude is V_{AG}. These two variables are estimated from a previous harmonic balance (HB) analysis. Then, the circuit variables are expressed in the form $\sum_K X_k(t)e^{jk\omega_{AG}t}$. At the node N, due to the connection of the AG X_l will be constant in the interval [0,T]. However, at the time T, the AG is disconnected from the circuit, this enabling its evolution to the actual solution. In case of a periodic oscillation, the phasors will be of the form $x_k(t) = X_K e^{jk(\omega_0-\omega_{AG})t}$, with X_K being a complex constant and ω_0-ω_{AG}, the frequency error. The fundamental frequency of the series expansion has, of course, to be updated after the analysis, to avoid, in case of a parameter sweep, an unnecessary reduction of the sampling rate of the envelopes, due to the frequency error. Note that the new AG technique simultaneously initializes all the circuit nodes. It takes advantage of the inherent flexibility of the time-domain expression of the phasors and enables an efficient analysis of the oscillator versus perturbations and noise, not requiring any demanding calculation time varying AG values $V_{AG}(t)$, $\omega_{AG}(t)$ during the resolution process.

The envelope transient approach with the initialization technique has been applied to the push-push oscillator. For illustration, two AGs with different amplitude values have been considered (although only one is necessary for the analysis). This enables providing different initial conditions to the two oscillators. (Fig. 3a.). The AGs are disconnected at the time t=50ns. From that time, the two oscillators naturally evolve to the synchronized solution.

A realistic design requires the prediction of the effect of inequalities in the circuit-element values on the first-harmonic cancellation. For this analysis, some representative parameters have been swept in a small interval about the intended value. As an example, the influence of the transistor base resistance is analyzed in Fig. 3b. It shows the evolution of the first-harmonic amplitude at each collector terminal The perfect cancellation occurs for $r_{b1}=r_{b2}=15\ \Omega$. For $r_{b1}=18\ \Omega$ an instability is observed. Although a nodal harmonic balance formulation is used , the Nyquist stability criterion has been applied to check that the observed response is not due to a numerical instability of the technique [6]. Instability has actually been obtained from the Nyquist analysis.



(a)



(b)

Fig. 3. (a) Application of the new initialization technique for the analysis of the push-push oscillator. Different AG values were given in each oscillator circuit. The two AGs are disconnected ad time t=50ns. (b) Evolution of the circuit solution versus r_{b1}.

It must be noted that, when oscillators are not symmetric, there is a limited synchronization bandwidth, which explains experimental observations of quasi-periodic solutions. For r_{b1}=18 Ω, a Hopf bifurcation gives rise to a loss of synchronization, with the two sub-circuits oscillating at different frequencies f_0 and $f_0+\Delta f_0$. The small frequency shift is Δf_0=4 MHz, and gives rise to narrow envelopes about $k\omega_0$. In injected oscillators, the Hopf bifurcations are typically encountered for relatively high injection power. Here, each oscillator is an injection oscillator for the other one; which explains why it is this kind of bifurcation which leads the circuit to a quasi-periodic regime.

The variation of other representative parameters has been considered in Fig. 4, showing the effect of inequalities in r_{b1} and the lengths of the collector and emitter microstrip lines on the output power at the first harmonic component. As can be seen, the perfect cancellation is very critical in all cases, with the unbalance in the length of the collector line having the biggest impact on the output power. Taking into account the accuracy in the line construction, an output power of about –30 dBm at f_0 should be expected. This prediction technique, which can be extended to any circuit parameter, can help reduce criticality if comparison of different implementations of a particular element are carried out.

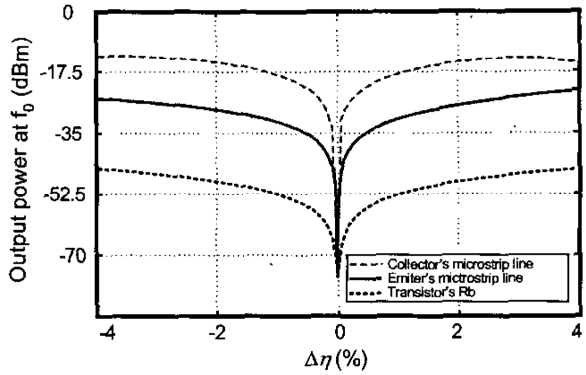


Fig. 4. Variations in the output power at the fundamental frequency f_o, versus percentage of inequalities.

IV. PHASE-NOISE ANALYSIS

The phase noise of the push-push oscillator has been analyzed through harmonic balance and using the envelope transient, in similar way to [5]. For the analysis, two noise sources are considered in each transistor: a current source at the base terminal, accounting for flicker and shot noise, and another current source, at the collector terminal, for the shot noise. The noise sources of the two transistors are considered uncorrelated.

In the HB analysis, a combination of the carrier modulation approach and the conversion matrix approach (for larger frequency offsets) is used [7]. In the carrier modulation approach, the variations of the oscillation frequency, due to the noise perturbations, are calculated by linearizing the mixed-mode harmonic balance system about the steady-state oscillation [7]. In the envelope-transient analysis, the noise inputs are considered as a summation of pseudo-sinusoids, applying superposition [5]. The results of both analysis are shown in Fig. 5. As can be seen, good agreement is obtained between the two techniques. Although not represented, the push-push configuration provides a phase noise improvement close to the 3 dB of the theoretical predictions [1,2].

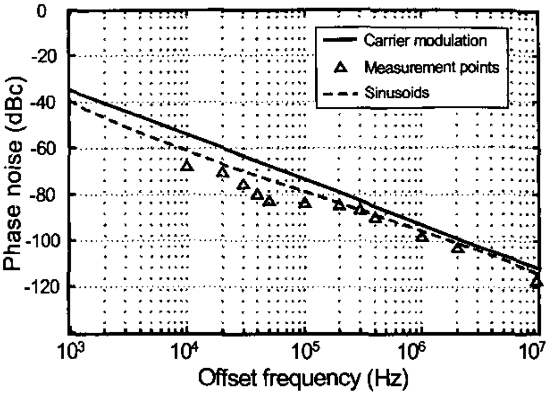


Fig. 5 Comparison between the phase noise spectrum calculated using the envelope transient technique. Measured results were superimposed for validation.

V. Oscillator Implementation And Measurement

The demonstrator has been implemented on plastic substrate (Cuclad™ 2.17) using specific microwave drilling tools instead of chemical processes, in order to match the physical dimensions of the lines. For maximum symmetry, one of the devices has been back-mounted to allow the same line dimensions at each oscillator. The accuracy in the line length is 50 μm, which constitutes about 0.5% in the width and length of the microstrip lines. The resulting output power spectrum is shown in Fig. 6.

The output power at the second harmonic agrees with the prediction of the nonlinear design in Fig. 2. On the other hand, the output power at the fundamental frequency is in the order of the predictions by the sensitivity analyses of Fig. 4. Finally, the phase noise measurements at the output frequency $2f_o$ have been superimposed on the simulated spectra of Fig. 5, with very good agreement.

VI. Conclusion

Detailed non-linear simulation techniques for push-push oscillators have been presented. A harmonic-balance technique enables the optimum selection of the circuit element values for maximum output power at the second harmonic component. The oscillator and its sensitivity to circuit inequalities is analyzed through the envelope transient approach, using a new initialization technique of the circuit variables, which enables an efficient application of the envelope transient approach to oscillator circuits. The output phase noise of the push-push oscillator is also determined through the approach. The techniques have been verified on a 18 GHz push-push oscillator, with very good agreement with experimental results.

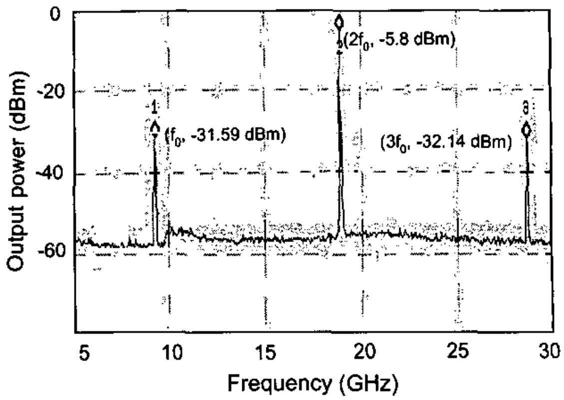


Fig. 6. Experimental output power spectrum of the push-push oscillator.

Acknowlegment

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