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LETTER TO THE EDITOR

Subharmonic injection-locking and self-oscillating mixing

F. Plessas[1,*,†], A. Papalambrou[2] and G. Kalivas[2]

[1]*Department of Telecommunications Science and Technology, University of Peloponnese, Tripoli, Greece*
[2]*Department of Electrical and Computer Engineering, University of Patras, Rion 26500, Greece*

SUMMARY

Subharmonic injection-locking and self-oscillating mixing functions of a modified Colpitts oscillator operating at 1 GHz are reported. The injection-locking circuit, using a GaAs FET, is described theoretically and experimentally. Phase noise, power consumption and conversion gain measurements indicate that the proposed design is attractive for low-cost, low-power consumption front-ends. Copyright © 2008 John Wiley & Sons, Ltd.

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KEY WORDS: injection-locking; self-oscillating mixing; phase noise; harmonic mixing

1. INTRODUCTION

Subharmonic injection-locking is an approach to generate a stable harmonic of a pure reference signal. A free-running oscillator is locked by the nth harmonic of an injected signal, generated by the nonlinearities of the active device [1–4]. The injected signal inserts an additional phase shift (φ) into the feedback loop of the oscillator. The tank can no longer oscillate at the free-running frequency because the total phase shift at this frequency deviates from 2π (Barkhausen criterion) by φ. If the amplitude and the frequency of the injected signal are chosen properly, the tank cancels the effect of φ by oscillating at the injection frequency and injection-locking occurs [5].

A free-running oscillator also operates as a self-oscillating mixer (SOM) when the injected signal, which is applied at the RF/IF input, is outside the locking range [6–12]. In this case, the input signal, IF or RF, mixes with the LO produced by the same component (or the harmonic of the LO) to generate the output signal, RF or IF, respectively. SOMs eliminate the need for an LO source, decreasing power consumption and cost while increasing compactness.

*Correspondence to: F. Plessas, Department of Electrical and Computer Engineering, University of Patras, Rion 26500, Greece.
†E-mail: plessas@ee.upatras.gr

Sub-harmonic injection-locking is widely used for synchronization, high-gain amplification and phasing of microwave oscillators in communication electronics and phased arrays. Phase noise improvement of injection-locked oscillators (ILOs) [1] compared with free-running oscillators [13–15] demonstrates the importance of injection-locking. In addition, SOMs are cost efficient and easy-to-integrate circuits. The minimum number of components reduces the cost, whereas the compact solution offers easier integration. They are used in radar systems, radiometry, imaging applications, communication systems, transceiver front-ends, etc. Furthermore, subharmonic injection-locked self-oscillating mixers (s-ILSOM) combine both subharmonic injection-locked oscillation and mixing functions: the synchronized LO results in an output signal having a high spectrum purity. Typically, such devices operate as Doppler detectors, in fundamental or in subharmonic mode. Reduced size and low consumption allow for using them in applications such as active-phased array antennas or in injection-locked phase-locked loops where the VCO and the phase detector (mixer) functions may be served by the same device.

In this letter, we report the design and experimental results of a novel architecture, combining both the oscillation and the mixing functions in a single module (Figure 1(a)), which can be locked by injecting an external signal. At the same input as the one used for the injection we may apply the IF or RF signal when the circuit is used as a mixer. Consequently, providing suitable signals at the injection port and RF/IF input, it implements mixing and harmonic mixing simultaneously (with positive up-conversion gain), free-running oscillation, injection-locked oscillation and subharmonic injection-locked oscillation.

In contrast to previously reported works, the novel s-ILSOM provides mixing and harmonic mixing simultaneously with positive up-conversion gain and increased carrier-to-noise ratio. In our approach, s stands for the fourth subharmonic signal that is used to stabilize the oscillation signal. Furthermore, both the injection and the RF/IF signals are applied at a common point (input) and a buffer is used to isolate the load.

Calculated results using the derived formula for the locking range and phase noise are presented, whereas detailed experimental results for phase noise, locking range, up- and down-conversion gain, and power consumption are provided.

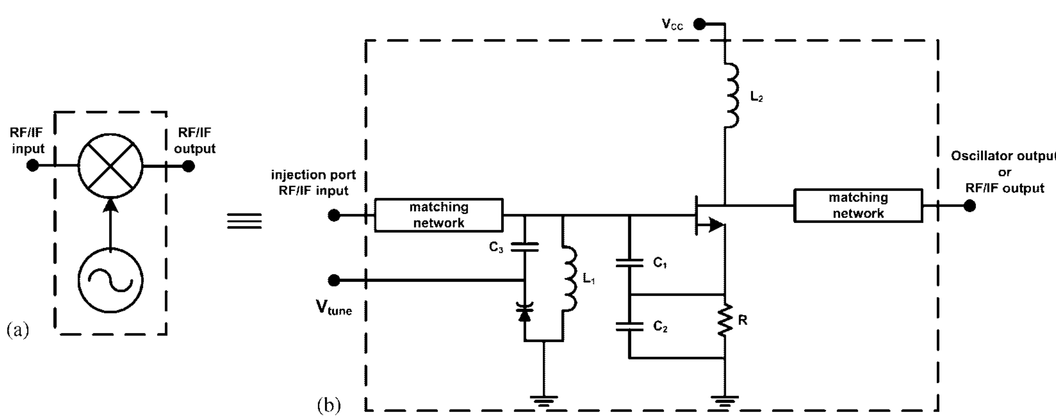

Figure 1. Typical up- and down-conversion configuration (a) and the proposed circuit (b).

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2. DESIGN

Most of the reported work [5, 16, 17] for ILOs is based on the analytical model using one-port networks. In contrast to the above, we develop a two-port ILO, which functions also as an SOM under unlocked conditions without any modification. Furthermore, only one input is required, whereas in [6] two inputs for the SOM operation are used. The proposed topology, shown in Figure 1(b), is a simple Colpitts oscillator operating in the free-running mode when no signal is applied at the injection (RF/IF input) port. If an external signal within the locking range is applied at the input, the circuit operates as an ILO. Furthermore, if the injection signal is at a subharmonic of the free-running frequency, then the proposed circuit functions as a subharmonic ILO. Under the case that the external signal is outside of the locking range, both fundamental self-oscillating mixing and harmonic self-oscillating mixing are realized. Finally, the last and most important mode of operation is implemented by using a coupler at the input, at which both an injection-locking signal—to stabilize the LO portion of proposed circuit—and an RF/IF signal are applied simultaneously.

The full locking range is proportional to the power of the injected signal $\sqrt{P_{\text{inj}}}$ [1]. Calculations show that when injected with the subharmonic ($n=2$) the locking range varies from 15 KHz ($P_{\text{inj}}=-30\,\text{dB m}$) to 3.5 MHz ($P_{\text{inj}}=-10\,\text{dB m}$). For $n=4$, the respective locking range varies from 10 KHz ($P_{\text{inj}}=-26\,\text{dB m}$) to 0.7 MHz ($P_{\text{inj}}=-10\,\text{dB m}$).

Applying the method of [1] to the circuit under test, we obtain the phase noise of the s-ILO as

$$\mathscr{L}(f)=\frac{\Delta f^2 \mathscr{L}_{\text{inj}}(f)\cos^2\varphi}{\Delta f^2\cos^2\varphi+4f^2}+\frac{4f^2\mathscr{L}_{\text{osc}}(f)}{\Delta f^2\cos^2\varphi+4f^2} \tag{1}$$

where φ is the stationary phase difference between the free-running oscillator and the reference signal, f is the offset carrier frequency and $\mathscr{L}_{\text{osc}}(f)$ and $\mathscr{L}_{\text{inj}}(f)$ are the single-sideband spectral densities of the phase noise of the free-running oscillator and the reference signal, respectively. Using actual measurements for the phase noise of the reference and the free-running oscillator, the phase noise of the s-ILO is calculated and presented graphically in Figure 2. The subharmonic ($n=2$ and 4) reference signals, although at different frequencies, have the same phase noise profile.

The proposed circuit as described earlier also operates as an SOM and a harmonic SOM simultaneously, under unlocked conditions. The desired $f_{\text{RF}}=nf_{\text{LO}}-f_{\text{IF}}$ or $f_{\text{IF}}=nf_{\text{LO}}-f_{\text{RF}}$ ($n=1$ and 2) is extracted from the RF/IF output. Simulations were performed for this mode of operation, by applying a low-power injection signal ($\approx -20\,\text{dB m}$) at a subharmonic of the oscillation frequency ($f_{\text{LO}}/4$) together with the RF or the IF signals. The circuit operates as an s-ILSOM, providing considerable improvement in carrier-to-noise ratio for the resultant output signal.

3. PERFORMANCE

A hybrid version of the circuit, using a GaAs FET, is designed and fabricated on a PTFE substrate with a relative dielectric constant of 6.15 and a thickness of 10 mil. Elemental values are given in Table I.

Furthermore, the input and output matching networks consist of cascaded microstrip lines and parallel open stubs.

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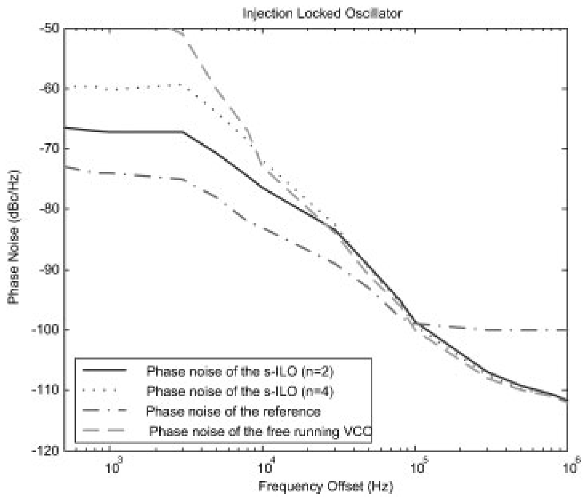

Figure 2. Calculated phase noise of the s-ILO. The injected signals are at 480 and 240 MHz (same phase noise profile) with a −20 dB m power level.

Table I. Elemental values.

Transistor	NE38018, CEL
Varactor	MA46H200 M/A-COM
PCB	e_r : 6.15
	Thickness: 10 mil
C_1, C_2	15 pF
C_3	22 pF
L_1	1 nH
L_2	10 mH

Phase noise and conversion gain measurements were obtained using a vector signal analyzer (HP 89410A) and spectrum analyzers (TEK 2712, E4407B), whereas the injection and the IF signals are generated by a commercial synthesizer (HP 8648C). A typical two-tone IP3 measurement was performed, and finally, regarding NF, a noise figure analyzer, a noise source and a signal generator were used.

The measured phase noise of the free-running VCO is −60 dB c/Hz at 5 KHz. In the s-ILO mode of operation, the component showed a large phase noise reduction (Figure 3), with 12 dB improvement when a 480 MHz at −20 dB m injection signal is applied at the gate and 5 dB improvement when a 240 MHz signal at −20 dB m is applied. The calculated and measured phase noise levels are in relatively good agreement. The measured locking range is 3 MHz, for $n=2$ subharmonic injection, and 0.6 MHz, for $n=4$ subharmonic injection, at a power level of −10 dB m.

Mixing characteristics of the s-ILSOM mode of operation are also measured as shown in Figure 4. Using a coupler, we applied an IF signal at 174 MHz and a 240 MHz signal to stabilize the generated oscillation signal at 960 MHz ($n=4$ subharmonic injection). The resulting RF signals are at 786 and 1746 MHz. Up- and down-conversion gains are measured as a function of IF or RF input.

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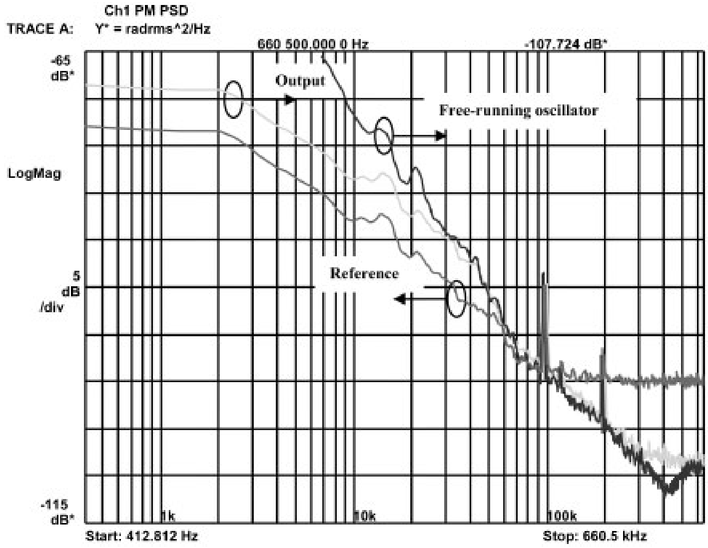

Figure 3. Measured phase noise of the s-ILO in the case of subharmonic injection locking. The injected signal is at 480 MHz with a −20 dB m power level.

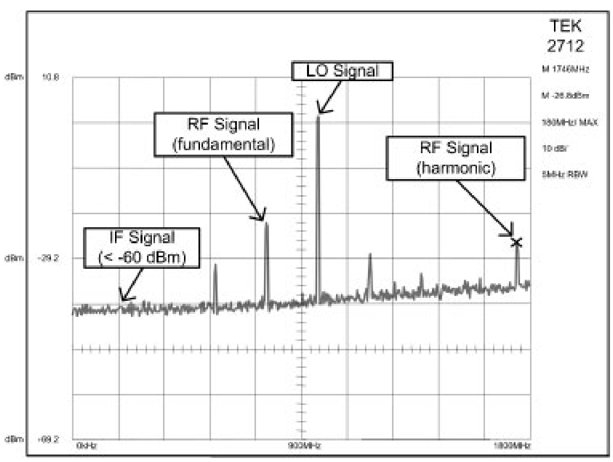

Figure 4. Measured power spectrum of the s-ILSOM in the case of IF signal up-conversion. The IF signal is at 174 MHz with a −34 dB m power level.

A 13 dB up-conversion and a −3 dB down-conversion gains are measured for fundamental mixing, at 786 MHz, whereas 7 dB up-conversion and a −9 dB down-conversion gains are measured for harmonic mixing, at 1746 MHz. Furthermore, the IF/RF isolation is 29 dB, the oIP3 is −5 dB m, the $P_{1\,dB}$ is −18 dB m, the NF is 9.4 dB and the improvement in carrier-to-noise ratio is 20 dB at 5 KHz. Finally, the power consumption is only 24 mW using a 3 V supply.

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4. CONCLUSION

A novel, high-performance, multifunction circuit has been demonstrated. It implements VCO, injection-locking and mixing functions, fundamental and harmonic simultaneously, providing a phase noise improvement of 5 dB (for $n=4$ subharmonic injection) to 12 dB (for $n=2$ subharmonic injection) at 5 KHz offset and an up-conversion gain of 7 dB (harmonic mixing) to 13 dB (fundamental mixing), consuming only 24 mW of power from a single 3 V supply.

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