A Subharmonic Injection-Locked Self-Oscillating Mixer

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Abstract—A subharmonic injection-locked self-oscillating mixer (s-ILSOM) at 1 GHz is reported in this paper. The proposed circuit which combines both injection-locking and mixing functions is described theoretically and experimentally. In contrast to previously reported works, only one input port is required for both the RF/IF signal and the injection signal. Furthermore, the injection signal which is used to stabilize the oscillation is at a subharmonic of the oscillation frequency ($f_{LO}/4$), with a power level as low as -20 dBm. Phase noise calculations and mixing characteristics are reported, indicating a noise improvement, and a high up-conversion gain for both fundamental and harmonic mixing. The circuit is implemented, using a GaAs FET, exhibiting an up-conversion gain of 13 dB, a phase noise of -93 dBc/Hz at 100 KHz offset, a P_{1dB} of -18 dBm, an IP3 of -5 dBm, and a power consumption of 24 mW.

I. INTRODUCTION

Self oscillating mixers (SOMs) are attractive due to their reduced size, cost and power consumption [1-4]. They implement both the oscillation and mixing functions simultaneously. However, these circuits are not tunable and their carrier-to-noise ratio is limited by the poor phase noise and stability of the oscillator portion. Previous works employ one more input port to apply a reference signal, used to synchronize the oscillation signal generated by the same component, forming in this way an injection-locked self-oscillating mixer (ILSOM)

A subharmonic injection-locked self-oscillating mixer (s-ILSOM) combines both subharmonic injection-locked oscillation and mixing functions [5], [6]. Typically, such devices operate as Doppler detectors, in fundamental or in subharmonic mode. Furthermore, reduced size and consumption allows for using them in applications such as active phased array antennas, or in injection-locked phase-locked loops (LPLLs) [7], where the VCO and the phase detector (mixer) functions may be served by the same device [8].

Regarding SOMs, earlier works described a 500 MHz SOM based on a push-pull differential amplifier, using two inputs located at different points, one for the RF/IF signals and one for the injection [1], and a 2.5 GHz cross-coupled SOM using again two different inputs [3]. An optical injection locking self-oscillating mixer is presented in [4], whereas a subharmonic self-oscillating mixer for 60 GHz applications is reported in [5]. The generated LO frequency is at 30 GHz while a doubling mechanism is introduced to generate the 2nd harmonic. Finally, an s-ILSOM used in a phase conjugation circuit is demonstrated in [6], where the SOM oscillates at its fundamental frequency, whereas the injected signal is at a subharmonic (÷2) frequency.

This paper, describes the design and experimental results of a novel s-ILSOM which provides mixing and harmonic mixing simultaneously with positive up-conversion gain and increased carrier-to-noise-ratio. In our approach, s- stands for the ÷4 subharmonic signal which 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. In addition, detailed experimental results for phase noise, locking range, up- and down-conversion gain, noise figure, P_{1dB}, IP3, and power consumption are provided.

The basic formulation of the s-ILSOM is described in Section II among with calculated and simulation results. Performance and experimental results are given in Section III, whereas Section IV, provides concluding remarks on the design and measurements.

II. SYSTEM DESIGN

The proposed circuit is based on a modified Colpitts oscillator, as shown in Fig. 1. We present the theoretical expressions for the phase noise, when the SOM is stabilized by a subharmonic (÷4) injection signal.

Most of the reported work for the phase noise analysis of oscillators and injection-locked oscillators is based on the analytical model, using one-port network, presented by Adler [9], Kurokawa [10] and extended by Razavi [11]. However, our analysis is based on a two-port network, whereas the injection signal is applied at the gate of the active device and the stabilized signal is extracted from the drain. Furthermore, in contrast to [1] and [3] the proposed s-ILSOM has only one input for both the IF/RF signal and the injection signal. Using a coupler, the injection locking signal to stabilize the LO portion of proposed circuit and the RF/IF signal can be

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applied simultaneously. Due to the fact that we use a ÷4 subharmonic injection, the IF and the injection signals are relatively close in frequency, allowing for the design of a single matching network. Regarding down-conversion, to avoid matching problems at the input, the injection signal can be applied at the fundamental frequency. In this case we need a very low power signal (-40 dBm).

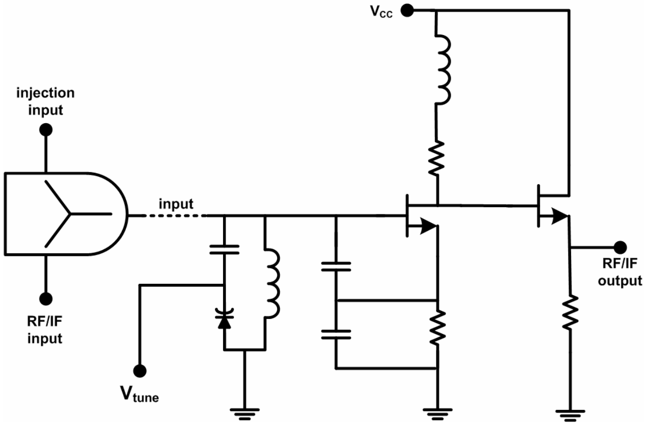
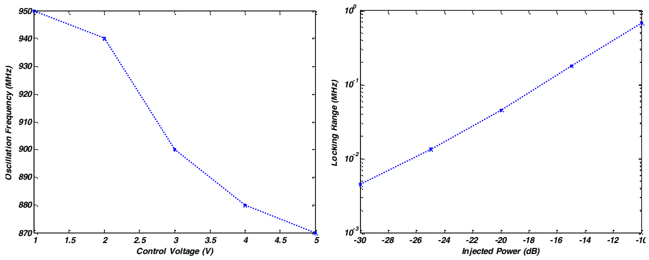


Fig. 1. *Schematic diagram of the proposed s-ILSOM.*

The oscillation frequency can be tuned using V_{tune}. As shown in figure 2(a) the oscillation signal (f_{LO}) varies from 870 to 950 MHz. Furthermore, it can be stabilized to an external signal (f_{INJ}) if:

$$f_{INJ} = \frac{f_{LO}}{4} \pm \frac{f_0}{2Q}\frac{V_4}{V_0} \qquad (1)$$

where V_4, V_0, f_0 and Q, are the harmonic (x4) voltage response of the injected signal, the voltage of the free-running signal, the free-running frequency, and the quality factor of the resonator respectively. The second term of the right-hand side of (1), $\Delta f/2$ is half the locking range. Δf varies with the injected power from 10 KHz (P_{inj} = -26 dBm) to 0.7 MHz (P_{inj} = -10 dBm) as shown in Fig. 2(b).



(a) (b)

Fig. 2. *Oscillation frequency versus control voltage (a) and full locking range versus injected power for a 240 MHz injected signal (b).*

Applying the method of [12] to the proposed circuit, after some mathematical manipulations, we obtain the phase noise of the oscillation signal as:

$$\mathcal{L}(f) = \frac{\Delta f^2 \mathcal{L}_{inj}(f)\cos^2\varphi}{\Delta f^2\cos^2\varphi + 4f^2} + \frac{4f^2\mathcal{L}_{osc}(f)}{\Delta f^2\cos^2\varphi + 4f^2} \qquad (2)$$

where φ is the stationary phase difference between the free-running oscillator and the injected signal, f is the offset carrier frequency, $\mathcal{L}_{osc}(f)$ and $\mathcal{L}_{inj}(f)$ are the single-sideband spectral densities of the phase noise of the free-running oscillator and the injected signal respectively.

From measurements, we obtain the phase noise of the injected $\mathcal{L}_{inj}(f)$ and the free-running oscillation signal $\mathcal{L}_{osc}(f)$, and using eq. (2) we calculate the phase noise of the stabilized oscillation signal $\mathcal{L}(f)$, when subharmonic injection is applied. A synthesized generator is used, providing a reference signal with a phase noise of -77 dBc/Hz at 5 KHz offset, whereas the phase noise of the oscillation signal without injection is -57 dBc/Hz. The results are presented in Fig. 3.

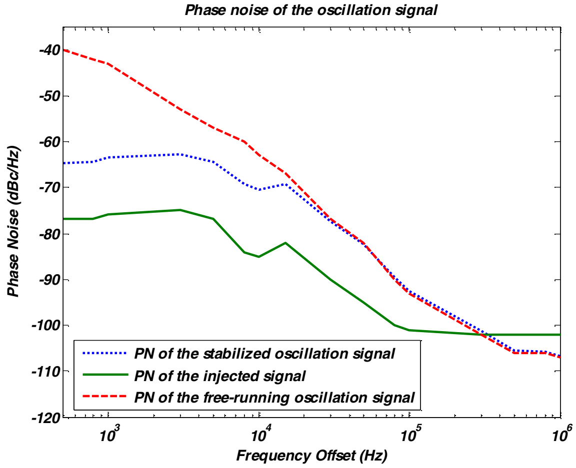


Fig. 3. *Calculated phase noise of the oscillation signal when a 240 MHz injection signal with -20 dBm power level is applied.*

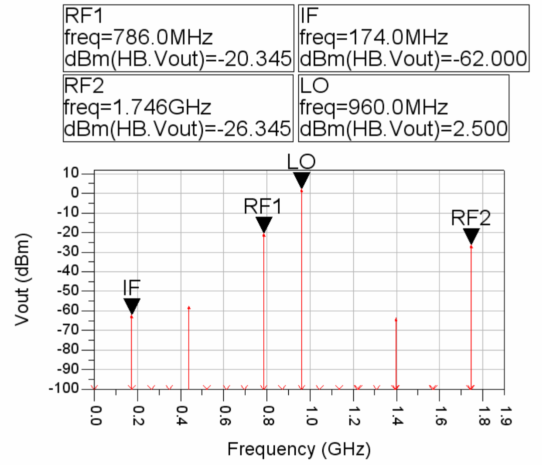


Fig. 4. *Simulated output spectrum of the mixer for an IF at 174 MHz with a -34 dBm power level.*

If the IF or the RF signals are not within the locking range, the stabilized oscillation signal will intermodulate with them to form an s-ILSOM. A harmonic balance simulation was performed to analyze the mixing characteristics of the proposed circuit. Used as an up-converter the output frequencies appearing at the RF/IF output port are at $f_{RF}=nf_{LO}-f_{IF}$ (n=1, 2), whereas used as a down-converter the output frequencies are at $f_{IF}=nf_{LO}-f_{RF}$ (n=1, 2).

As shown in Fig. 4 the generated oscillation signal is at 960 MHz with +2.5 dBm output power. An IF signal at 174 MHz with a power level of -34 dBm is used, producing RF1 at 786 MHz and RF2 at 1746 MHz. The calculated IF/RF isolation is 28 dB, the up-conversion gain is 14 dB for the fundamental mixing and 8 dB for the harmonic mixing.

Down-conversion simulation produced a conversion loss of 3 dB and 9 dB for n=1 and n=2 respectively.

III. PERFORMANCE AND MEASUREMENTS

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 mils. The measured phase noise of the free-running oscillation signal is -57 dBc/Hz at 5 KHz. Appling an injection signal at 240 MHz with a -20 dBm power level the proposed circuit showed a considerable phase noise reduction at low frequency offsets as shown in Fig. 5. The calculated and measured phase noise levels are in relatively good agreement.

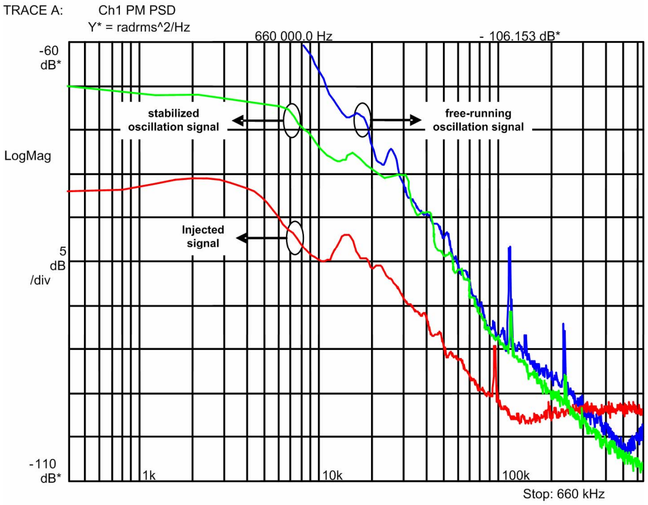


Fig. 5. *Phase noise improvement of the oscillation signal for a 240 MHz at -20 dBm injection signal.*

The measured locking range varies from 3.5 KHz for a subharmonic (÷4) injection signal of -30 dBm to 600 KHz for an injection signal of -10 dBm. Tuning range, tuning gain, output power, phase noise and power consumption of the s-ILSOM with and without injection signal are given in Table I.

To evaluate the effects of subharmonic injection-locking, the RF output spectrum is measured when no external signal is applied at the injection input port. Figure 7 shows the carrier-to-noise improvement when compared to Fig. 6.

TABLE I. OSCILLATION CHARACTERISTICS

	Oscillation Characteristics	
	Free-running oscillation signal	***Stabilized oscillation signal***[a]
Tuning range	875-955 MHz	(875-955) ± 0.03 MHz
Tuning gain	16 MHz/V	16 MHz/V
Output power	2 dBm	2 dBm
Power consumption	24 mW	24 mW
Phase noise@5 KHz	-57 dBc/Hz	-67 dBc/Hz

[a] 240MHz, -20 dBm injection.

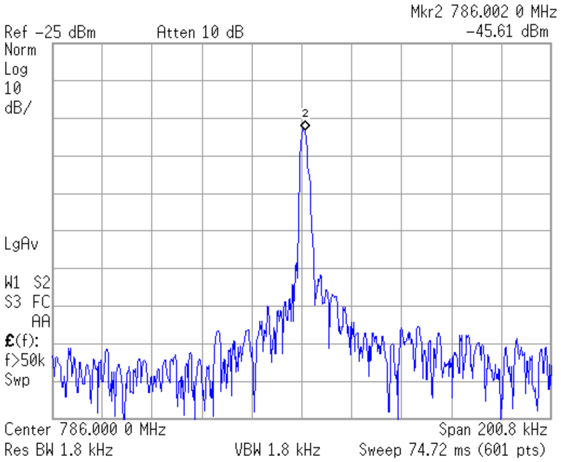


Fig. 6. *RF output spectrum of the s-ILSOM without an injection signal.*

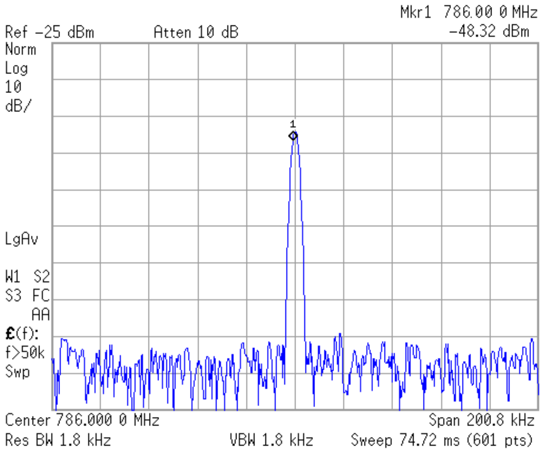


Fig. 7. *RF output spectrum of the s-ILSOM with an injection signal at 240 MHz with a -20 dBm power level.*

Mixing characteristics of the SOM portion are also reported. Up- and down-conversion gains are measured for fundamental and harmonic mixing. For fundamental mixing the up-conversion gain is 13 dB and the down-conversion loss is 4 dB. In addition, for harmonic mixing the corresponding gain and loss for up- and down-conversion are 7 dB and 10.5 dB respectively. The output spectrum observed for the case of up-conversion is presented in Fig 8. Applying two tones, one at the IF/RF input and another at the injection port, the *OIP3* was calculated using the measured power of one of the tones at the output p_{o1}, and the difference between the power of this tone and the 3rd order products $p_{o1} - p_{o13}$.

$$OIP_3 = p_{o1} + \frac{|p_{o1} - p_{o13}|}{2} \tag{3}$$

The 1 dB compression point and the conversion gains are also measured and the results are presented in Table II.

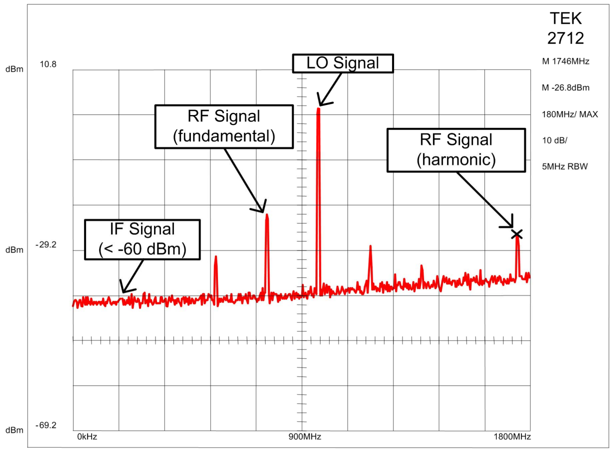


Fig 8. *Measured output spectrum of the s-ILSOM where both the fundamental and the harmonic mixing products are presented.*

TABLE II. s-ILSOM P_{1dB}, OIP3, AND CONVERSION GAIN

	s-ILSOM Performance			
	***F_{LO}* (MHz)**	***P_{1dB}* (dBm)**	***IP3* (dBm)**	***CG* (dB)**
Up-conversion	875-955	-18	-5	13
Down-conversion	875-955	-21	-8	-4
Up-conversion^{b}	1740-1900	-26	-13	7
Down-conversion^{b}	1740-1900	-28	-15	-10.5

b. harmonic mixing.

Finally, the measured NF is 9.4 dB and the power consumption is only 24 mW using a 3 V supply.

IV. CONCLUSION

This work demonstrates the theoretical analysis and experimental results of a novel high-performance subharmonic injection-locked self-oscillating mixer at 1 GHz. Only one input is used for both the injection and the IF/RF signals. Furthermore, a subharmonic of the free-running oscillation frequency at 240 MHz with -20 dBm of power level was used to stabilize the oscillator and reduce the phase noise by 10 dB at 5 KHz. Measurements of the mixing functions indicated an up-conversion gain of 7 dB, for the harmonic mixing at 1746 MHz, and 13 dB for the fundamental mixing at 786 MHz. The RF/IF isolation is 29 dB, the phase noise -93 dBc/Hz at 100 KHz offset, the P_{1dB} is -18 dBm, the IP3 is -5 dBm, and the power consumption is only 24 mW.

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