A 5-GHz Subharmonic Injection-Locked Oscillator and Self-Oscillating Mixer

Fotis C. Plessas, *Member, IEEE*, A. Papalambrou, *Member, IEEE*, and G. Kalivas, *Member, IEEE*

***Abstract*—This paper presents a multifunctional circuit realizing the functions of oscillation, mixing, amplification, and frequency multiplication at 5 GHz. A theoretical and experimental description of the circuit is given. The proposed circuit, which combines both the injection-locking and mixing processes, uses only one port where both the RF/intermediate frequency signal and the injection signal (IS) are applied. The IS, which is used to stabilize the oscillation, is at a subharmonic of the oscillation frequency $(\omega_{\rm osc}/4)$ having a power level as low as -50 dBm. Calculations of the phase noise and measurements of the mixing properties are reported which indicate a noise improvement, and a high up-conversion gain. The implementation of the circuit exhibits an up-conversion gain of 14 dB, a phase noise of -110 dBc/Hz at 100-kHz offset, a $\mathrm{P}_{1\ \mathrm{dB}}$ of -15 dBm, a third-order intercept point of -2 dBm, and a power consumption of 35 mW. Calculated and measured results are in good agreement for all cases, emphasizing the relevance of the proposed circuit.**

***Index Terms*—Injection-locked oscillator (ILO), phase noise, self-oscillating mixer (SOM).**

I. Introduction

MULTIFUNCTIONAL circuits configured to realize functions like oscillation, mixing, amplification, and frequency multiplication have become very attractive due to their smaller size, higher performance, improved reliability, reduced power consumption and lower cost. A number of different techniques and approaches could be used to build such a circuit, like injection locking or self-oscillating mixing.

Injection locking [1]–[3] is an approach to lock the state of a free-running oscillator by injecting an external signal of low phase noise. The frequency of the external signal must be within the operating frequency range of the oscillator at the fundamental or a subharmonic of the required output frequency [subharmonic injection-locked oscillator (ILO)] [4], [5]. Furthermore, self-oscillating mixers (SOMs) simultaneously implement both the oscillation and mixing functions [6]–[8]. Their reduced size, cost and power consumption makes them an attractive choice for system designers. These circuits, however, lack the function of being tunable and have a reduced carrier-to-noise ratio, limited by the poor phase noise and stability of the oscillation portion. In previous works, one more input port is used to apply a reference signal. In this way, an injection-locked SOM (ILSOM) is formed by the synchronization of the oscillation signal generated by the same active element [9]–[11]. Subharmonic ILSOMs (s-ILSOMs) combine both subharmonic injection-locked oscillation and mixing functions [12]–[14]. Such devices operate typically as Doppler detectors, in fundamental or in subharmonic mode. Their reduced size and small consumption permits their use in applications such as active phased array antennas or in injection-locked phase-locked loops (ILPLLs) [15], where the same device may serve as VCO and phase detector. 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/intermediate frequency (IF) signals and one for the injection [6], and a 2.5-GHz cross-coupled SOM using two different inputs as well [7]. An optical injection locking SOM is presented in [9], whereas a subharmonic SOM for 60-GHz applications is reported in [13]. The generated local oscillator (LO) frequency is at 30 GHz while a doubling mechanism is introduced to generate the second harmonic. Finally, an s-ILSOM used in a phase conjugation circuit is demonstrated in [14], where the SOM oscillates at its fundamental frequency, whereas the injected signal (IS) is at a subharmonic $(\div 2)$ frequency.

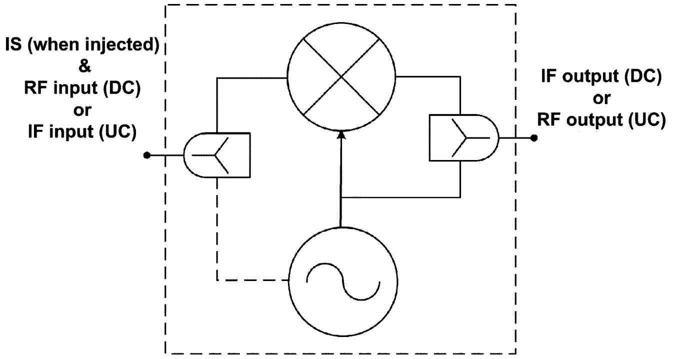

Fig. 1. Functional block diagram of the proposed circuit.

In this work, we extend the work done in [12] where we presented a 1-GHz s-ILSOM. Here, we propose a novel multifunctional circuit operating at 5 GHz, which provides injection-locked oscillation, self-oscillating mixing, and injection-locked self oscillating mixing with high up-conversion gain and reduced carrier-to-noise ratio. Furthermore, it functions as a free-running oscillator and as a frequency multiplier $(\times 2, \times 4)$ and amplifier. Finally, the theoretical analysis of the proposed circuit is presented.

In our approach, we use a $\div 4$ subharmonic signal, (s- stands for the $\div 4$) for stabilizing the oscillation signal by injection. In

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F. C. Plessas is with the Department of Telecommunications Science and Technology, University of Peloponnese, Tripoli 22100, Greece, and also with the Applied Electronics Laboratory, Department of Electrical and Computer Engineering, University of Patras, 26500 Rio, Greece (e-mail: fplessas@uop.gr; plessas@ee.upatras.gr).

A. Papalambrou and G. Kalivas are with the Department of Electrical and Computer Engineering, University of Patras, 26500 Rio, Greece (e-mail: papalambrou@ieee.org; kalivas@ee.upatras.gr).

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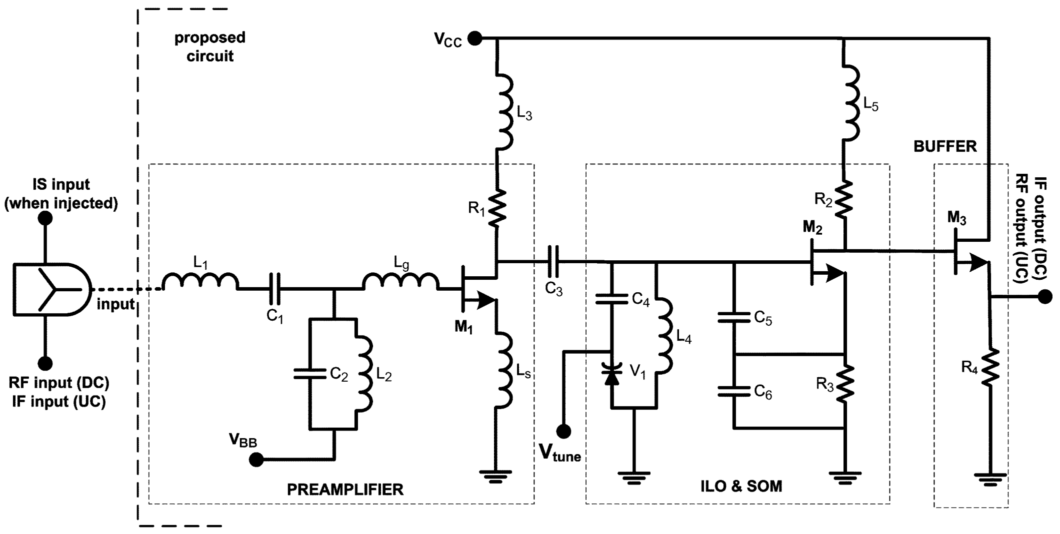


Fig. 2. Proposed multifunctional circuit.

this way, when the circuit operated as a s-ILSOM for up-conversion the IF signal and the IS are close in frequency, requiring only one single matching network present at the input. Furthermore, and in contrast to previous works, both the IS and the RF/IF signals are applied at a common point (input) with a buffer isolating the load. Last but not least, the proposed circuit incorporates all functions reported separately by [5]–[12]. A functional block diagram of the circuit illustrating all functions is shown in Fig. 1. At the input, the IS is applied (when injected), together with the IF signal when the circuit is used as an up-converter (UC), or the RF signal when is used as a down-converter (DC). Correspondingly, the IF signal appears at the output in the down-conversion process, while the RF signal is created at the output when the circuit is used for up-conversion.

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, $\mathrm{P}_{1\ \mathrm{dB}}$, third-order intercept point (IP3), and power consumption are provided. Section II describes the proposed circuit including analysis and simulations, followed by implementation and measurement results in Section III. In Section IV summary and conclusions are presented.

II. CIRCUIT AND SIMULATION

The proposed multifunctional circuit is composed of three major building blocks, i.e., a preamplifier, an ILO/SOM, and a buffer, as shown in Fig. 2. The preamplifier in the first stage is implemented as a common source low-noise amplifier, providing sufficient gain for the (÷4 subharmonic) IS to synchronize the oscillator. The ILO and SOM block is a modified Colpitts oscillator functioning as: 1) a free-running oscillator; 2) an ILO; 3) an SOM; 4) an ILSOM; or 5) a frequency multiplier/amplifier depending on the applied signals at the input. Finally, the output buffer is a source follower added to isolate output loading from the oscillator/mixer. The oscillation signal (ω_{osc}) can be tuned by using V_{tune}. Moreover, we apply the IS at the gate of the active device whereas we extract the stabilized signal from the drain. Table I summarizes the functions of the proposed circuit depending on the signals applied to the IS and RF/IF input.

TABLE I
CIRCUIT FUNCTIONS

	Function	IS (MHz)	RF (MHz)	IF (MHz)
1	free running oscillator	-	4100-4200	-
2	injection locked oscillator	4100-4200	4100-4200	-
3	sub-harmonic injection locked oscillator (÷2)	2050-2100	4100-4200	-
4	sub-harmonic injection locked oscillator (÷4)	1025-1050	4100-4200	-
5	self oscillating mixer	-	5050-5450	950-1250
6	injection locked self oscillating mixer	2050-2100	5050-5450	950-1250
7	sub-harmonic injection locked self oscillating mixer	2050-2100 / 1025-1050	5050-5450	950-1250
8	frequency multiplier (x2) & amplifier	2050-2100	4100-4200	-
9	frequency multiplier (x4) & amplifier	1025-1050	4100-4200	-

In agreement with Fig. 1, RF represents input for down-conversion operation and output for up-conversion operation, whereas, IF represents input for up-conversion operation and output for down-conversion operation. Most of the reported work for the phase noise analysis of oscillators and ILOs is based on the one port analytical model presented by Adler [2], Kurokawa [3] and extended by Razavi [1]. A two-port network, however, is the basis for our analysis.

Considering operation of the circuit as an ILO or s-ILO (functions 2, 3, 4 of Table I), an external IS (ω_{inj}) is used to stabilize the output frequency ω_{osc}. The IS inserts an additional phase shift (φ) into the feedback loop of the oscillator. The tank can no longer oscillate at the free running frequency ω_{osc} because the total phase shift at this frequency deviates from 2π (Barkhausen criterion) by φ. If the amplitude and the frequency of the IS are chosen properly the tank cancels the effect of φ by oscillating at the injection frequency and injection locking occurs.

When injecting a sinusoid signal with a frequency of ω_{inj} and an amplitude of V_{inj}, the nth harmonic with a frequency of $n\omega_{inj}$ and an amplitude of V_{outn} is inherently produced by the nonlinearities of the circuit. If $\omega_{\rm osc} = n \cdot \omega_{inj} \pm \Delta\omega_n$, ($\Delta\omega_n = (\omega_{\rm osc}/2Q)(V_{outn}/V_{\rm out})$ is half the locking range, [2]) the oscillator synchronizes with (the nth harmonic) and thus improves its phase noise characteristics. The total phase noise of the ILO originates from the free-running oscillator phase noise and the IS phase noise. Extending the analysis presented by Kurokawa [3] for the fundamental mode of operation, we calculate the total noise for the subharmonic ILO. Neglecting the phase noise of the IS the phase noise of the locked oscillator is calculated as

$$\mathcal{L}(\omega) = \frac{\left(2Q\frac{\omega}{\omega_{\rm osc}}\right)^2}{\left(2Q\frac{\omega}{\omega_{\rm osc}}\right)^2 + \left(\frac{V_{outn}}{V_o}\right)^2 \cos^2\varphi}\mathcal{L}_{\rm osc}(\omega) \qquad (1)$$

or

$$\mathcal{L}(\omega) = S_1\mathcal{L}_{\rm osc}(\omega). \qquad (2)$$

If the IS contains noise then the output phase noise at a frequency offset of ω with respect to the input phase noise would be

$$\mathcal{L}(\omega) = \frac{n^2\left(\frac{V_{outn}}{V_o}\right)^2 \cos^2\varphi}{\left(2Q\frac{\omega}{\omega_{\rm osc}}\right)^2 + \left(\frac{V_{outn}}{V_o}\right)^2 \cos^2\varphi}\mathcal{L}_{\rm inj}(\omega) \qquad (3)$$

or

$$\mathcal{L}(\omega) = n^2 S_2\mathcal{L}_{\rm inj}(\omega). \qquad (4)$$

We note that $S_1 + S_2 = 1$ and that the total phase noise is given by S_1 times the phase noise of the free-running oscillator plus $n^2 S_2$ times the phase noise of the IS. Thus

$$\mathcal{L}(\omega) = \frac{\left(2Q\frac{\omega}{\omega_{\rm osc}}\right)^2}{\left(2Q\frac{\omega}{\omega_{\rm osc}}\right)^2 + \left(\frac{V_{outn}}{V_o}\right)^2 \cos^2\varphi}\mathcal{L}_{\rm osc}(\omega) + \frac{n^2\left(\frac{V_{outn}}{V_o}\right)^2 \cos^2\varphi}{\left(2Q\frac{\omega}{\omega_{\rm osc}}\right)^2 + \left(\frac{V_{outn}}{V_o}\right)^2 \cos^2\varphi}\mathcal{L}_{\rm inj}(\omega) \qquad (5)$$

where $\mathcal{L}_{\rm osc}(\omega)$ and $\mathcal{L}_{\rm inj}(\omega)$ are the single-sideband spectral densities of the phase noise of the free-running oscillator and the IS, respectively. φ is the stationary phase difference between the free-running oscillator and the IS given by $\phi = \sin^{-1}(\delta\omega/\Delta\omega_n)$. In our case, φ is close to ±90° which means that the frequency of the IS is close to the edge of the locking range which represents the worst case in terms of phase noise. Fig. 3 shows the computed phase noise profile based on (3). For the computation, the measured phase noise of the free-running oscillator and the measured phase noise of the 1.25-GHz reference signal have been used. The phase noise improvement is 30 dB at 1 kHz, 20 dB at 5 kHz, and 10 dB at 10 kHz.

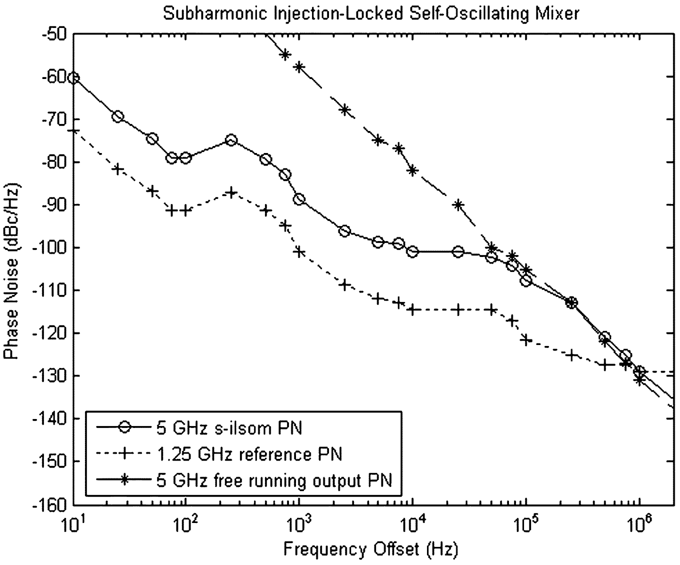


Fig. 3. Phase noise of the 5-GHz s-ILSOM.

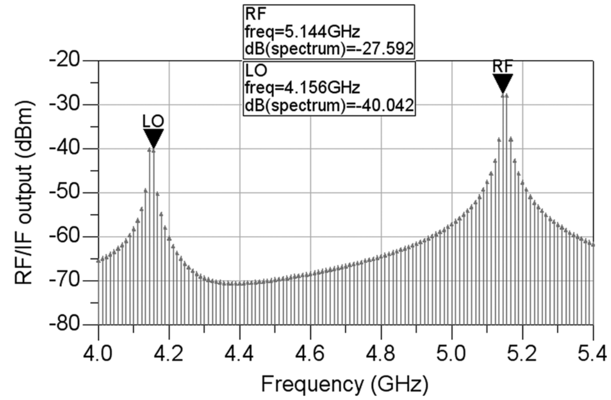
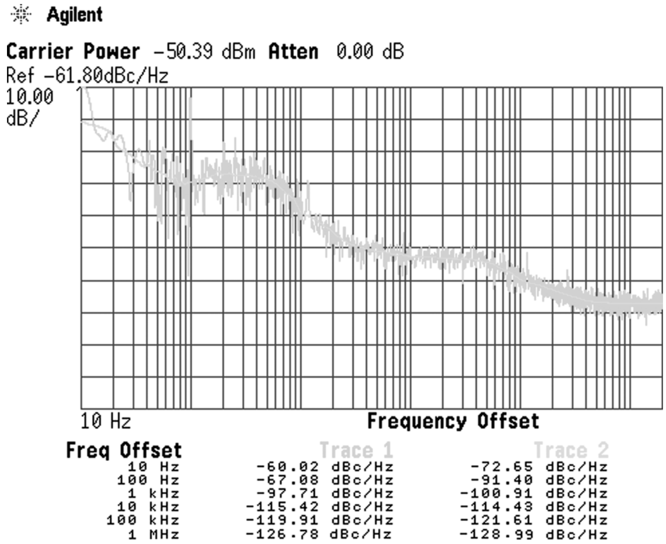


Fig. 4. Output spectrum (up-conversion).

In the case that the IF or the RF signal at the input falls out of the locking range, it will intermodulate with the stabilized oscillation signal forming an s-ILSOM (functions 6, 7 of Table I). The proposed s-ILSOM uses only one input for both the IF/RF signal and the IS which contrasts previous work (for example [6] and [7]). Since a ÷4 subharmonic injection is used, the IF and the IS are adequately close in frequency. This fact allows us to design a single matching network at the input of the preamplifier.

To analyze the mixing characteristics of the proposed circuit a harmonic balance simulation was performed. When used as an up-converter the output frequencies appearing at the RF/IF output port are at $\omega_{\rm RF} = \omega_{\rm osc} + \omega_{\rm IF}$, whereas when used as a down-converter the output frequencies are at $\omega_{\rm IF} = \omega_{\rm osc} - \omega_{\rm RF}$. As shown in Fig. 4 the generated oscillation signal is at 4156 MHz with −40-dBm output power. An IF signal at 988 MHz with a power level of −40 dBm is used, producing RF at 5144 MHz. The calculated IF/RF isolation is 28 dB and the up-conversion gain is 14 dB. Furthermore, simulation of down conversion showed a conversion gain of 2 dB.



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Carrier Power -50.39 dBm Atten 0.00 dB
Ref -61.80dBc/Hz

Freq Offset        Trace 1            Trace 2
     10 Hz      -60.02 dBc/Hz      -72.65 dBc/Hz
    100 Hz      -67.08 dBc/Hz      -91.40 dBc/Hz
     1 kHz      -97.71 dBc/Hz     -100.91 dBc/Hz
    10 kHz     -115.42 dBc/Hz     -114.43 dBc/Hz
   100 kHz     -119.91 dBc/Hz     -121.61 dBc/Hz
     1 MHz     -126.78 dBc/Hz     -128.99 dBc/Hz
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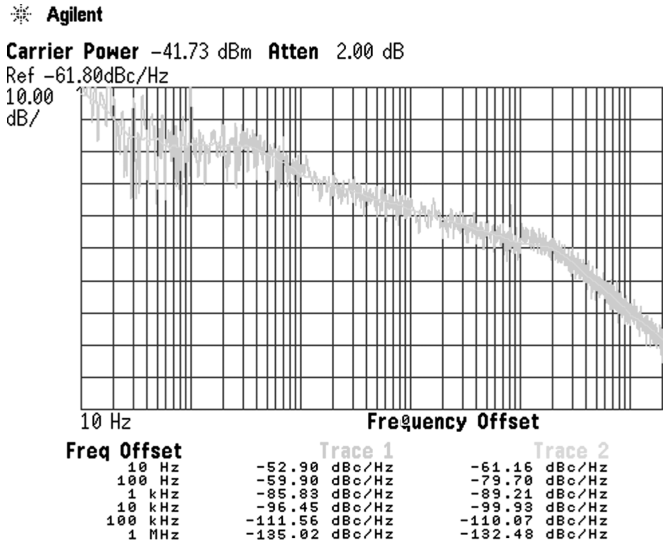
Fig. 5. Phase noise of the reference.



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Carrier Power -41.73 dBm Atten 2.00 dB
Ref -61.80dBc/Hz

Freq Offset        Trace 1            Trace 2
     10 Hz      -52.90 dBc/Hz      -61.16 dBc/Hz
    100 Hz      -59.90 dBc/Hz      -79.70 dBc/Hz
     1 kHz      -85.83 dBc/Hz      -89.21 dBc/Hz
    10 kHz      -96.45 dBc/Hz      -99.93 dBc/Hz
   100 kHz     -111.56 dBc/Hz     -110.07 dBc/Hz
     1 MHz     -135.02 dBc/Hz     -132.48 dBc/Hz
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Fig. 6. Phase noise of the proposed circuit.

III. MEASUREMENT RESULTS

We designed a hybrid version of the circuit, using GaAs field-effect transistors (FETs) and a GaAs hyperabrupt tuning varactor, fabricated on polytetrafluoroethylene (PTFE) substrate with a relative dielectric constant of 6.15 and a thickness of 10 mils. This allows for rapid implementation and provides flexibility in design optimization.

Phase noise of the free-running oscillation signal was measured at -72 dBc/Hz at 5 kHz. After applying an IS at 1250 MHz with a -50-dBm power level, produced from a synthesized source (Fig. 5), a considerable phase noise reduction of the proposed circuit was measured at low-frequency offsets as shown in Fig. 6. The calculations and measurements of the phase noise levels are in relatively good agreement.

Some functions are performed simultaneously (i.e., sub-harmonic injection-locking and self-oscillating mixing resulting in an s-ILSOM). The input of the ILO and SOM needs to be matched over a wide frequency range covering all the frequencies given in Table I. The inductive source-degeneration method along with a passband filter structure is a commonly used technique allowing the synthesis of a real part for the input impedance in a broadband range while resonating the reactive part of the input impedance over the whole band (wide-band matching). The measured S11 satisfies the condition of less than -10 dB over the frequency spectrum of 900 MHz to 5.5 GHz.

TABLE II
OSCILLATION PERFORMANCE

Tuning range	4100-4200 MHz
Tuning gain	20 MHz/V
Output power	-40 dBm
Power consumption	17 mW
Phase noise@5 KHz	-72 dBc/Hz (free-running) -95 dBc/Hz (injection-locked)

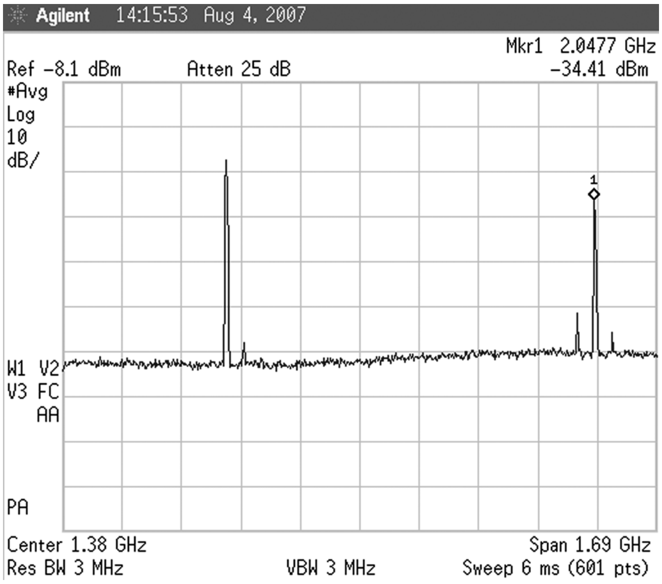

Fig. 7. Output spectrum (down-conversion).

The measured locking range variation was from 3.7 kHz for a subharmonic (÷4) IS of -45 dBm to 1000 kHz for an IS of -10 dBm. In Table II we present the tuning range, tuning gain, output power, phase noise, and power consumption of the s-ILSOM with and without IS.

Regarding mixing characteristics of the SOM portion, up- and down-conversion gains are measured. An up-conversion gain of 14 dB is measured whereas the down-conversion gain is 2 dB.

The output spectrum of the mixer when an RF signal of -30 dBm at 5150 MHz is applied at the RF/IF input is shown in Fig. 7. Furthermore an injection-locking signal of -50 dBm at 1250 MHz is applied at the IS port. The tone at the left-hand side of Fig. 7 corresponds to the produced IF signal of -25 dBm whereas the tone at the right-hand side of Fig. 7 corresponds to the harmonic ($\times 2$) of the injection-locking signal.

The output spectrum observed for the case of up-conversion is presented in Fig. 8. The IF signal of -43 dBm at 1000 MHz and the oscillation signal of -41 dBm tuned at 4150 MHz, produce an RF signal of -29 dBm at 5150 GHz. This results to a conversion gain of 14 dB.

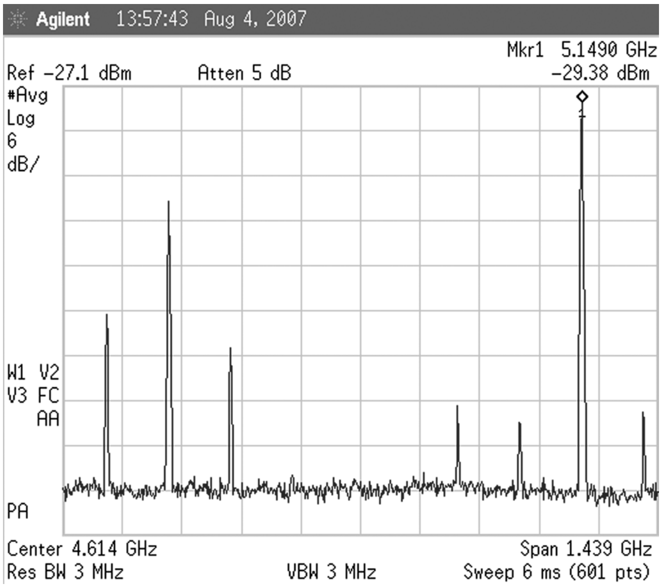

Fig. 8. Output spectrum (up-conversion).

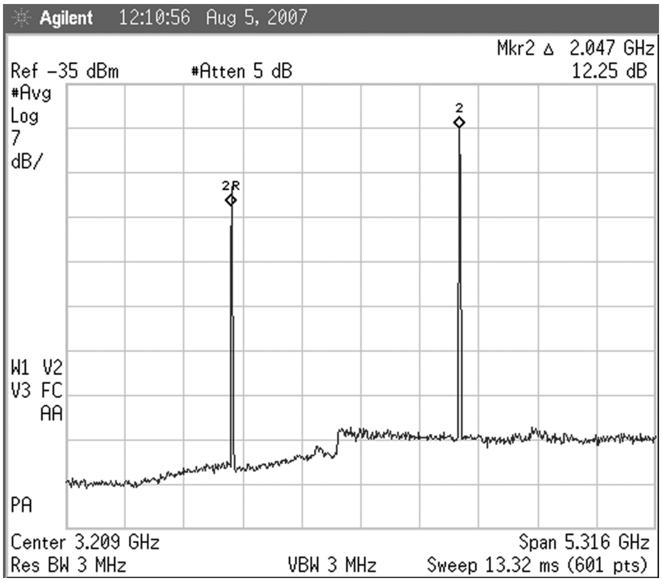

Fig. 9. Output spectrum (frequency multiplier).

TABLE III
MIXING PERFORMANCE

	P_{1dB} *(dBm)*	*IP3 (dBm)*	*CG (dB)*
up-conversion	-15	-2	14
down-conversion	-19	-6	2

Fig. 9 shows the output spectrum of the proposed multifunctional circuit when it functions as a frequency doubler/amplifier. The input signal is at 2050 MHz with a power level of −52 dBm, while the output signal is at 4100 MHz with a power level of −40 dBm.

Furthermore, the 1-dB compression point and the IP3 are also measured and the results are presented in Table III. Finally, the measured noise figure (NF) is 8.9 dB and the power consumption is only 35 mW using a 3-V supply.

IV. CONCLUSION

In this work, a multifunctional circuit was proposed realizing a variety of operations. These include oscillation, fundamental and subharmonic injection-locked oscillation, fundamental and subharmonic injection-locked self-oscillating mixing, and frequency multiplication/amplification. Experimental results demonstrated high performance operation in all modes of the implemented circuit at 5 GHz. In contrast to previous works, only one input is used for both the injection and the IF/RF signals. Furthermore, in order to stabilize the oscillator and reduce the phase noise by 20 dB at 5-kHz a subharmonic of the free-running oscillation frequency at 1250 MHz with −50 dBm of power level was used. When the circuit was used as s-ILSOM, measurements of the mixing functions indicated an up-conversion gain of 14 dB and a down-conversion gain of 2 dB. The RF/IF isolation is 29 dB, the phase noise −110 dBc/Hz at 100-kHz offset, the $\mathrm{P}_{1\ \mathrm{dB}}$ is −15 dBm, the IP3 is −2 dBm, and the power consumption is only 35 mW. All the above demonstrate a novel, multifunction front-end component with low power consumption, suitable for integration in high-performance radio transceivers.

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