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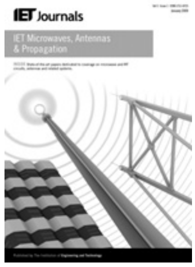
Published in IET Microwaves, Antennas & Propagation
Received on 23rd February 2014
Revised on 17th August 2014
Accepted on 12th September 2014
doi: 10.1049/iet-map.2014.0118



ISSN 1751-8725

Design of injection-locked oscillator circuits using an HBT X-parameters™-based model

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Abstract: A load independent X-parameters-based heterojunction bipolar transistor (HBT) model has been used for the first time in the design and behaviour prediction of injection-locked oscillator circuits. This model has been extracted from load-pull measurements with a large-signal network analyser and, in order to obtain a high oscillator RF power, targeting a load impedance close to the optimum one for HBT maximum output power. A methodology is given to obtain robust injection-locked oscillator circuits with a high-synchronisation bandwidth. Several injection-locked oscillator prototypes have been designed and fabricated, and their measurements compared with the simulations obtained using the X-parameters model. Satisfactory results were obtained when the prototypes were operated as free-running and synchronised oscillators.

1 Introduction

In order to design accurate complex non-linear microwave circuits, such as mixers, power amplifiers or oscillators, it is necessary to have available precise active device non-linear models.

Frequency-domain X-parameters-based behavioural transistor models have been demonstrated as accurate and efficient [1–3] for use in circuit design, even in the case of highly non-linear circuits, such as power amplifiers [3] and free-running oscillators [4, 5]. The penalty paid with respect to conventional compact models is that this accuracy in large-signal regime is restricted to device operating conditions similar to those used during model extraction (bias point, frequency or input power), therefore, the extrapolation capabilities are more limited than in compact models. Typically, the measurements required for behavioural model extraction demand expensive large-signal measurement systems, and are complex and sometimes time-consuming if we want to extend the model validity range.

In this paper, an X-parameters-based design methodology for injection-locked oscillators is proposed, following in part the methodology proposed in [5] for free-running oscillators, but including new steps in order to design injection-locked oscillators with a high-synchronisation bandwidth. For this purpose, heterojunction bipolar transistor (HBT) X-parameters behavioural models have been extracted from the measured response of a SiGe HBT (NESG2030M04) stimulated by a set of harmonically-related discrete tones, where the fundamental tone was dominant. The measurements have been performed using a mixed passive-active load-pull LSNA-based measurement system, targeting the fundamental output impedance around that required for maximum HBT RF output power. Several HBT-based oscillators have been designed and fabricated, and used to validate the behavioural model performance at different frequencies and input RF powers. In this paper, the measured behaviour of two different prototypes has been compared with simulations. Both oscillators have been designed to achieve the same output fundamental impedance and free-running oscillation frequency, but a slightly different oscillation output power, obtained by designing a different resonator (the same network with different values) in order to validate the injection-locked oscillator methodology proposed. The usefulness of X-parameters-based models in the design of injection-locked oscillators has been established, which was one goal in this work, and a new measurement-based design methodology was proposed.

Please, note this paper aims to provide the microwave circuit designer with a new practical and robust methodology to guide the design of injection-locked oscillators. This methodology is fully measurement-based, accurate and simple, in comparison to other previously proposed synchronised oscillator design procedures [6–12] being more thorough in terms of their theoretical background. Nevertheless, the new proposed methodology quickly provides a possible design solution, saving design simulation time. An in depth analysis of the obtained solution can later be performed by means of conventional methods (zero-pole identification, etc.) and/or further optimised, if required.

2 HBT X-parameters model

2.1 HBT X-parameters model formulation

The PolyHarmonic Distortion (PHD) model [1, 2] is a black-box frequency-domain behavioural approach that may be presented as an extension of the s-parameters black-box characterisation under large-signal conditions. This model uses the concept of harmonic superposition to analytically describe the large-signal B waves response of a non-linear system, linearised around a large-signal operating point, as functions of a linear mapping of the stimulus A waves (A_{qn}), in a similar manner as s-parameters. The basic load-independent (or fixed-load) model has the following mathematical formulation [13]

$$B_{pm} = X^F_{pm}(DC, |A_{11}|)P^m + \sum_{qn} X^S_{pm,qn}(DC, |A_{11}|)P^{m-n} \cdot A_{qn} + \sum_{qn} X^T_{pm,qn}(DC, |A_{11}|)P^{m+n} \cdot A^*_{qn} \quad (1)$$

where the model coefficients X^F_{pm}, $X^S_{pm,qn}$ and $X^T_{pm,qn}$ are the X-parameters, following the formulation and terminology introduced by Agilent in [13]; p and q are the port indexes (1, 2), $m = (1, 2, \ldots)$ and $n = (1, 2, \ldots)$ are the harmonic indexes; and $P = e^{j\angle A_{11}}$ and $|A_{11}|$ represents the large-signal fundamental input stimulus. If the device operation region is confined to a part of the Smith Chart around a selected reference (Z_{ref}), fundamental load impedance, where the X-parameters are determined, this allows for the extraction of an accurate 'local' model for circuit design.

2.2 HBT X-parameters model extraction

The established procedure for the X-parameters model extraction is similar to that proposed in [4]. The output spectral component (B_{pm}) has contributions from both A_{qn} and A_{qn}*, the two relative phases for the small-signal tones provide two independent data for the output spectral component (B_{pm}), that are sufficient to determine X^S and X^T coefficients for a given harmonic frequency component. Although three measurements are theoretically enough to extract the PHD model functions, it is desirable to perform more measurements in combination with a linear regression technique to reduce residual measurement errors. In order to extract this model, mixed active–passive load-pull measurements with an LSNA (Maury-NMDG) were performed by terminating, using the passive system, the device into a fundamental reference impedance ($Z_{ref} = Z_{opt} = 34 + 9.6j\ \Omega$, in this case, to provide the maximum fundamental device RF output power. In these conditions, a first set of power-dependent measurements were done. Then, the last set of measurements were performed by setting the output signal source (A_{21}), the open-loop active system, to a fixed power level and varying the input signal source phase between 0 and 2π, to cover an impedance area in the Smith Chart around the reference impedance Z_{ref}. Note that the injection level corresponding to A_{21} has been selected according to the results obtained in [4]. This procedure was also repeated for the harmonic components ($m = n = 3$). To predict the behaviour of an injection-locked oscillator, the X-parameters model must be dependent on both power and frequency. Thus, several measurements were performed versus frequency (from 4.5 to 5.5 GHz) and versus input power (from −30 to 6 dBm). As mentioned before, Z_{ref} is in this paper the optimum load impedance at fundamental frequency to provide transistor maximum output RF power, at 1 dB compression. This optimum impedance may change depending on the compression level we choose, as described in [5]. To obtain Z_{ref} and hence, an accurate X-parameters model around that impedance termination, we used the measurement-based search algorithm described in [14, 15], which couples X-parameters model extraction from measurements with analytical expressions based on X-parameters to predict power load-pull contours. In fact, we take advantage of the accuracy of the X-parameters measurements to predict load-pull contours to quickly locate the appropriate oscillator impedance design space on the Smith Chart, hence, speeding up the design. In [4] a X-parameters model was also extracted by terminating the device in 50 Ω ($Z_{ref} = 50\ \Omega$). Although the proposed design flow will utilise the model extracted targeting maximum output power, in this paper the predictions provided by both models will be compared in the following sections with measurements.

In Fig. 1 the Smith Chart region, which is covered by the load-pull extraction procedure performed for both models, is shown. Moreover, the simulated maximum power contours at 1 dB compression (obtained from a non-linear table-based model also extracted by the authors [16], and similar to the measured ones [15]) are shown. It can be seen that there is a large Smith Chart region in which differences in power are minimum. Also it is shown the output fundamental impedance Z_t, finally selected for both injection-locked (same impedance value) designs, after applying the proposed design methodology, and in the case of other targeted powers.

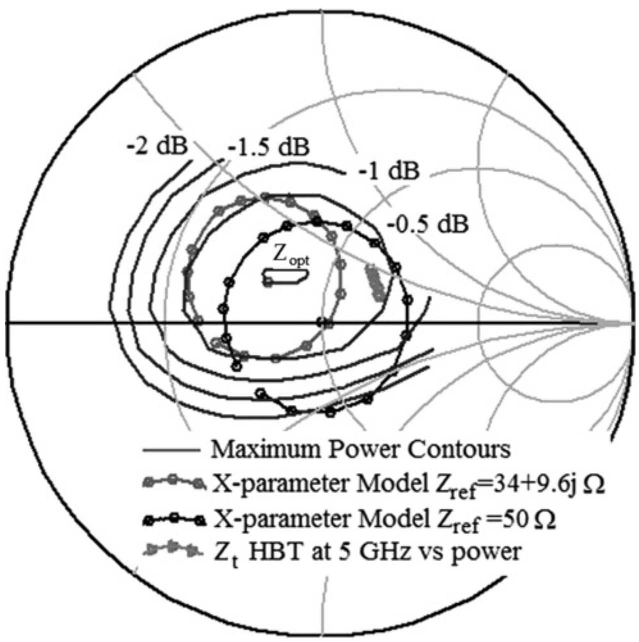

Fig. 1 *Plot of the HBT Z_{opt} for maximum RF output power (at 1 dB compression) and the corresponding power contours*

Grey and black circles show the range of impedances used for model extraction

Z_t is the HBT fundamental output impedance for oscillator design against input power

3 Injection-locked oscillator circuit design: a new design methodology

Injection-locked oscillators are circuits able to oscillate in the presence of an input periodic signal at the frequency ω_{in}. Thus, the oscillation frequency ω_o in free-running mode is influenced by the input signal and may take different ω_a values: $\omega_a/\omega_{in} = m/k$, with m and k integer values. The circuit oscillation is synchronised to the input signal frequency (or its multiples), thus for any change in the input signal frequency, the oscillation frequency changes, according to the previous relationship, by a complex non-linear phenomenon called synchronisation. In this work, the simplest synchronisation case is considered, in which $k = m = 1$. Therefore the oscillators are synchronised to the RF input signal. Applications of this type of injection oscillators are high-gain amplifiers and phase shifters [6]. The higher the difference between ω_a and ω_o the higher the input RF power required to maintain the synchronisation. At much higher or lower frequencies than the natural oscillation frequency, the synchronisation will be extinguished.

The injection-locked oscillator circuits shown in this work were designed combining the methodology proposed in [6] for injection-locked oscillators, to obtain robust prototypes and the methodology described in [5], to obtain high output power in free-running oscillators, incorporating new steps that take into account the injection-locked bandwidth requirement.

According to this new methodology, the injection-locked oscillators were initially designed as conventional free-running oscillators with an oscillation frequency around 5 GHz. Then, the external RF input signal with which the oscillators are synchronised, was applied to the resonator and other steps were followed, as will be explained in next section.

3.1 Injection-locked oscillation design procedure based on X-parameters

The first steps of the proposed methodology are common to those proposed for the design of two-port negative resistance free-running oscillator circuits [5]. Fig. 2 shows a circuit schematic of a two-port oscillator, in which some variables used in this work are defined. This schematic consists of a transistor, characterised by its X-parameters at a given bias point, a passive (load) network (Z_t), and a passive resonant (input) network (Z_{res}). When the circuit oscillates, the oscillation occurs at the same time at the input and output ports. Therefore, in the steady-state oscillation mode, conditions $\Gamma_{RES}.\Gamma_{IN} = 1$ and $\Gamma_T.\Gamma_{OUT} = 1$ are satisfied.

The design procedure used in this paper (Fig. 3 shows its flowchart) can be briefly described as follows:

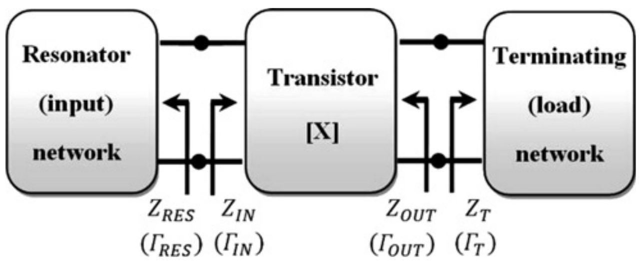

Fig. 2 *Two-port transistor oscillator schematic*

Step 1: Selection of a potentially unstable biased transistor able to provide the desired oscillation frequency and output RF power compatible with the specifications of the oscillator circuit.

Step 2: Finding the output impedance space. Selection of the appropriate transistor terminating (output reference) impedance, Z_{ref}, using the search iterative process described in [14], and experimentally validated in [15]. This impedance value is obtained in this procedure using

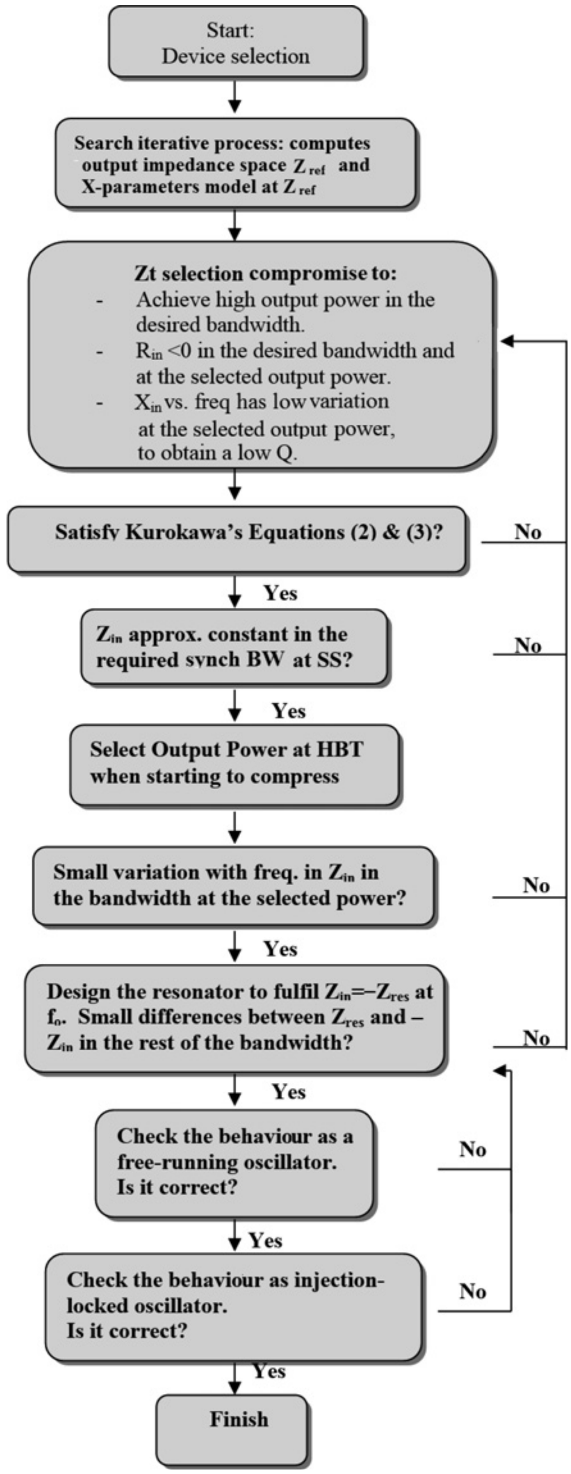

Fig. 3 *Proposed injection-locked oscillator design procedure*

Describing flowchart

IET Microw. Antennas Propag., 2015, Vol. 9, Iss. 4, pp. 380–388
doi: 10.1049/iet-map.2014.0118

measured X-parameters and load-pull power contours analytically computed from those measurements.

Step 3: Extracting the behavioural model. Extraction of the load-independent X-parameters transistor model, at the previously calculated Z_{ref}, to perform accurate predictions in the oscillator design impedance space (around Z_{ref}). This extraction is done, in fact, as part of the search iterative process (Step 2).

Step 4: Finding Z_t. Using the extracted X-parameters model, in this method, an appropriate terminating load (Z_t) is selected to obtain both high fundamental output RF power and high-synchronisation bandwidth. The search is confined around Z_{ref} value. Afterwards, the corresponding matching network to 50 Ω at the HBT output is designed, as well as a parallel feedback network to provide the necessary negative input resistance. It is also desirable to achieve a small variation, versus frequency, of the imaginary part of the input resistance (X_{in}) (especially at the desired output power) since the future resonator network will be then more easily designed to have a low Q, which allows for a high-synchronisation bandwidth. All these considerations guide the final Z_t selection whose value may be optimised in next steps. The selection of Z_t and the output RF power will result in a higher or lower variation of X_{in} with frequency, thus making possible to synchronise the oscillator in a wider or narrower bandwidth.

Step 5: Computing Z_{in}. Once the HBT terminating load was obtained, the computation of the corresponding HBT input impedance (with negative resistance) against output power is performed. It is mainly in this design step where the accuracy of the X-parameters model plays an important role. It is also crucial in the design that, besides obtaining a necessary negative input resistance, both real and imaginary parts of Z_{in} satisfy the simplified Kurokawa's (2) and (3), respectively, which relate to the non-linear behaviour of Z_{in} with the signal amplitude, as in [17].

$$\left.\frac{\partial R_{IN}(A)}{\partial A}\right|_{A=A_o} > 0 \qquad (2)$$

$$\left.\frac{\partial X_{IN}(A)}{\partial A}\right|_{A=A_o} < 0 \qquad (3)$$

Step 6: Analysing Z_{in}. It is necessary to verify that the behaviour of Z_{in} has a weak frequency dependence, since R_{in} is required to be negative in the synchronisation bandwidth, and lower X_{in} dependence with frequency will make possible to design a resonator network that will satisfy the oscillation conditions in the desired bandwidth. For this purpose, in first place, a simulation at small input power levels is performed. If the behaviour of both R_{in} and X_{in} is weak with frequency, a simulation of Z_{in} against power and frequency must be performed.

As the signal amplitude increases, the Z_{in} behaviour with frequency changes, as can be seen in Fig. 4, especially when the transistor starts to compress. The 'onset of compression' condition is very important, since Z_{in} is almost constant with frequency under linear conditions. Under compression, the absolute value of R_{in} changes with frequency due to the transistor non-linear nature. In order to obtain a high bandwidth, X_{in} dependence with frequency must be as small as possible and this is obtained when non-linearities are weak. For these reasons, to obtain both a high-output power and a high-synchronisation bandwidth, Z_t has to be close to Z_{opt} and the device should be just starting to compress. The higher the input power, the higher the variation of Z_{in} with frequency. This behaviour can be seen in Figs. 4*a* and *b* for R_{in} and X_{in}, respectively.

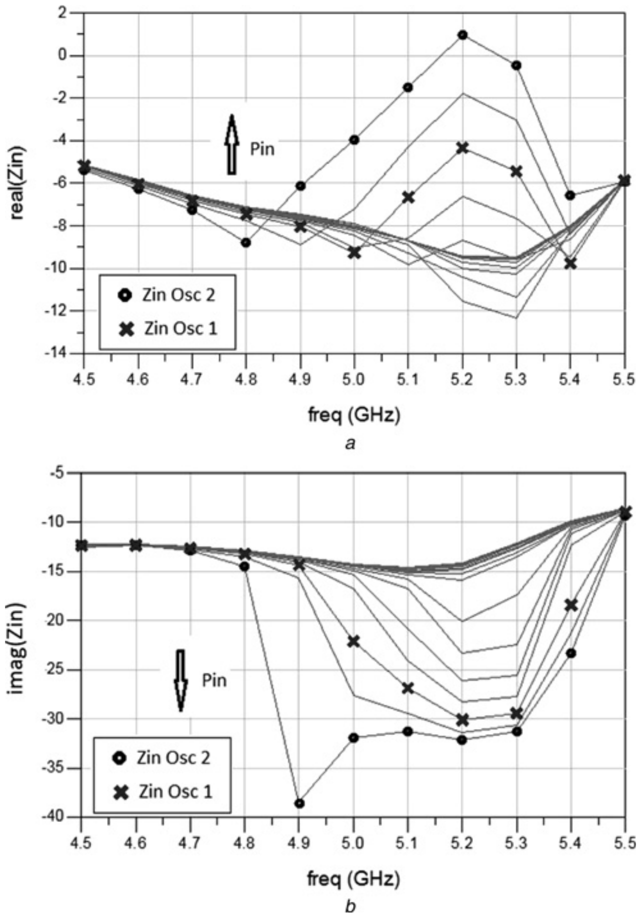

Fig. 4 *Z_{in} behaviour with input power and frequency*

a Real part
b Imaginary part
P_{in} = −9 to 3 dBm
Input impedance of oscillators 1 and 2 are represented with crosses and circles, respectively

Step 7: Final selection of Z_{in}. From previous step and Figs. 4*a* and *b*, it was determined that it is desirable to choose a Z_{in} value at the centre frequency (free-running oscillator frequency) for which the transistor is just starting to compress (a little less compression than P1 dB), to achieve high-output power and also high-synchronisation bandwidth. In this step Z_{in} is finally selected according to these considerations.

Step 8: Designing the resonator network. Once the desired output power is selected, the resonator is designed to present an impedance able to cancel the HBT input impedance, Z_{in}, thus enabling it to maintain the oscillation at the desired frequency and output power. Hence, the resonator must satisfy (4) and (5) at the desired power, where R_{RES} and X_{RES} are the real and imaginary parts of the resonator impedance. Moreover, the start-up condition for oscillation build-up is given by (6). It is also important to check that (4) and (5) are not fulfilled at other frequencies/power levels, because, if not, the designed injection-locked oscillator could oscillate, as free-running oscillator, at another different frequency to the desired one. As an external RF input signal, with which the oscillators are synchronised, is applied to the resonator, this part of the circuit is designed using a transmission line and a stub connected to a 50 Ω resistance (representing the input impedance of the RF source) through a λ/4 transformer, which enables the connection of the synchronising source without extinguishing the oscillation [6].

$$R_{IN}(A_o, w_o) + R_{RES}(w_o) = 0 \tag{4}$$

$$X_{IN}(A_o, w_o) + X_{RES}(w_o) = 0 \tag{5}$$

$$R_{IN}(A_o, w_o) + R_{RES}(w_o) < 0 \tag{6}$$

As can be seen in Fig. 3, if any of the previous steps do not meet the described requirements, a new Z_t is chosen. There are many impedances able to provide similar power performance, but each one provides different synchronisation bandwidths. At present, we do not have available an automatic procedure to find the optimum Z_t to simultaneously obtain both high-output power and bandwidth. Depending on the required synchronisation bandwidth and output power level, it might not be possible to obtain a Z_t fulfilling all the requirements. In this case, a compromise between synchronisation bandwidth and output power should be established.

3.2 Injection-locked oscillator prototypes designed using the proposed methodology

A schematic of the injection-locked oscillator circuits designed can be seen in Fig. 5. In this case, both the termination and resonator networks are made up from transmission lines and stubs. The feedback network is composed of a transmission line connected to ground through a capacitor.

In this work, the selected transistor is a SiGe HBT (NESG2030M04) that without the designed feedback network is stable at 5 GHz (at the selected bias point), and with the adequate terminating and feedback networks provides input negative resistance. In [5] the optimum load impedance for maximum output power for our HBT was calculated to be $Z_{ref} = 34 + 9.6j$, and a corresponding X-parameters model was extracted at Z_{ref}, by using a mixed passive–active load-pull LSNA-based measurement system. As demonstrated in previous papers by the authors [4, 5–14, 15], the model is able to correctly interpolate and extrapolate at other (close) output fundamental impedances around Z_{ref}. This is very important for oscillator design, since depending on the design or the targeted figures of merit the optimum output impedance will change.

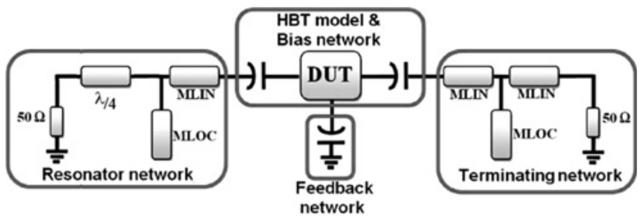

Fig. 5 *Schematic of the HBT-based injection-locked oscillator design*

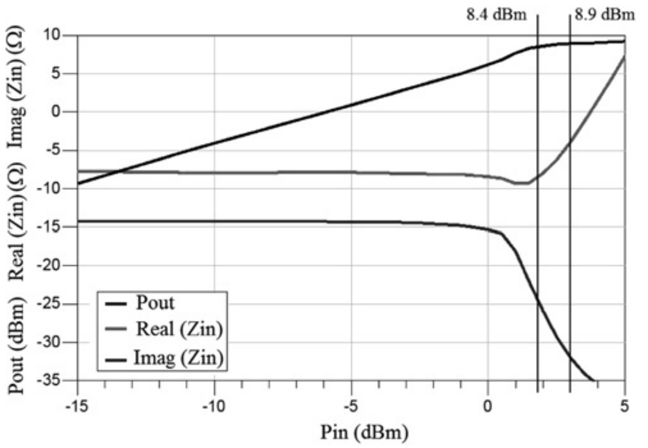

Fig. 6 *Simulations of the output power and the real and the imaginary parts of Z_{in} against input power*

In Fig. 6, the variation of Z_{in} (imaginary and real parts) and the oscillator output power as a function of the power at the input of the HBT, in the designed injection-locked oscillator, is shown. Note that these simulations are performed replacing the resonator by a 50 Ω signal source to drive the input power. In this figure, it can be seen that both R_{in} and X_{in} satisfy the simplified Kurokawa's equations. Conventional design methods based on small-signal s-parameters and only assuming a linear dependence of R_{in} with the signal amplitude, use (4) and (5) as steady-state oscillation conditions but, as can be seen in Fig. 6, R_{in} dependence with the signal amplitude is more complex, and the imaginary part of Z_{in} also has a large variation with the input signal amplitude. Thus, using (5) to obtain the resonator network may give poor estimations of the steady-state solution output power or oscillation frequency.

Two different input impedances (thus, oscillator output power values) were chosen at this point to validate the methodology proposed in previous section. The first one ($Z_{in1} = -9.2 - 1.9j$), provides an output power of 8.4 dBm, in which the HBT is starting to compress (and the negative input resistance is starting to decrease) and the other one ($Z_{in2} = -4.3 - 10.9j$), is optimised for a free-running oscillator targeting a higher output power; in this case 8.9 dBm.

In Figs. 4*a* and *b* the real and imaginary parts of Z_{in} are shown as a function of the frequency and input RF power. Z_{in1} and Z_{in2} at 5 GHz are also shown. As can be seen, the imaginary part of Z_{in2} presents a higher variation with frequency that Z_{in1}. Finally, two different resonators were designed, one to cancel Z_{in1} and the other Z_{in2}, using the same network but changing the line and stub lengths, obtaining in this way the oscillator circuits 1 and 2, respectively.

4 Results

Simulations of the designed circuits were performed in ADS using Harmonic Balance. When oscillators are simulated as free-running oscillators, a 50 Ω impedance is placed at the end of the resonator network. This 50 Ω resistance is taken into account when computing the transmission line and stub lengths. To simulate the oscillators, in synchronised mode, the 50 Ω resistance is replaced in the ADS schematic by a signal generator (P1_tone element in ADS), in order to

doi: 10.1049/iet-map.2014.0118

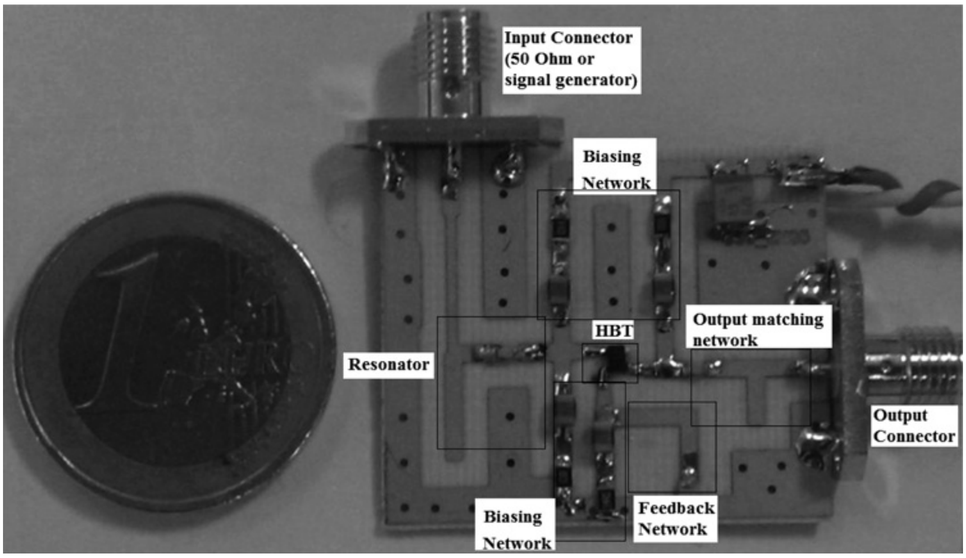

Fig. 7 *Photograph of the oscillator 1 prototype in HMIC microstrip technology*

sweep the input power and frequency as a synchronised oscillator, in the same way as in [6]. In Fig. 7 a photograph of the fabricated prototype, in HMIC technology, corresponding to oscillator 1 is shown. In Table 1, a comparison between measurements and simulations of the oscillator prototypes, in free-running oscillator mode, using the HBT X-parameters model (extracted at Z_{opt} and at 50 Ω) is shown. The simulated output power at the oscillation frequency for both prototypes are in agreement with the selected design power targets, identified in Fig. 6. In the comparison, it can be seen that there are slight differences between measured and simulated oscillation frequencies. The measured and simulated RF output power at the oscillation frequency is very close in both prototypes. Finally, some differences with respect to the measurements are found in the predictions of the second harmonic and, especially in the third harmonic. This may be related to the fact that the model extraction was performed with 50 Ω harmonics terminations, while both oscillators present other impedance values at the harmonics, especially the third one.

To demonstrate the prototypes behaviour as injection-locked oscillators, the 50 Ω load was removed and the prototypes connected to a microwave signal generator. Measurements were performed varying the input signal frequency and power, using a signal generator and a spectrum analyser. When measuring these circuits there are two possible outcomes. The first one is that the oscillator is synchronised; in this case there is only one tone at the synchronised frequency. The other possibility is that there are multiple tones: at the input frequency, at the free-running oscillation frequency and the corresponding mixing products. The oscillator 1 was also measured with the LSNA-based system calibrated from 4.3 to 5.5 GHz and 50 MHz span, and similar results were measured. However, in this case, it is not possible to know if there are signal components at the free-running oscillation and the corresponding mixing products, since the LSNA is just able to measure only the calibrated frequencies.

Figs. 8–10 show the measured and simulated results for the two injection-locked oscillator prototypes. In Figs. 8 and 10, the RF output voltage performance is shown as a function of frequency and input power. High values indicate that the oscillator is synchronised and low values indicate that it is not. Owing to the complexity of the three-dimensional representation in Fig. 8, new figures (Figs 9*a* and *b*) have been included with the purpose of clarifying the oscillator 1 performance. Hence, Fig. 9*a* shows the RF output voltage for a fixed synchronisation frequency against input power, whereas Fig. 9*b* shows the output voltage for a fixed input power against synchronisation frequency. These figures show the RF output voltage as in [6] (related to the output RF power and the 50 Ω load) in order to clarify the plots, with respect to power values, since lower differences between maximum and minimum values are achieved. In summary: oscillator 1 presents a much wider bandwidth than oscillator 2, but with less output power, as was expected according to the proposed design approach. Moreover, simulations and measurements are in agreement in both prototypes.

The model used in these simulations was obtained for a $Z_{\text{ref}} = 34 + 9.6j$ Ω, but very similar results were obtained with the one extracted at $Z_{\text{ref}} = 50$ Ω. The simulated output power and synchronisation bandwidth are close to the measured ones. Oscillator 1 bandwidth is close to the measurements, but slightly deviates in frequency. As can be seen in these

Table 1 HBT-based injection locked oscillators working as free-running oscillators: measurements against simulations

	Oscillation frequency, GHz	Output power, dBm	Second harmonic, dBm	Third harmonic, dBm
oscillator 1 simulations (34 + 9.6*j*) Ω	5.0	8.4	−14.1	−14.5
oscillator 1 simulations 50 Ω	5.0	8.5	−13.5	−14.7
measured oscillator 1	4.92	8.2	−14	−23
oscillator 2 simulations (34 + 9.6*j*) Ω	5.0	8.9	−12.9	−13.5
oscillator 2 simulations 50 Ω	5.0	8.9	−10.9	−13.8
measured oscillator 2	5.02	8.8	−12	−5.6

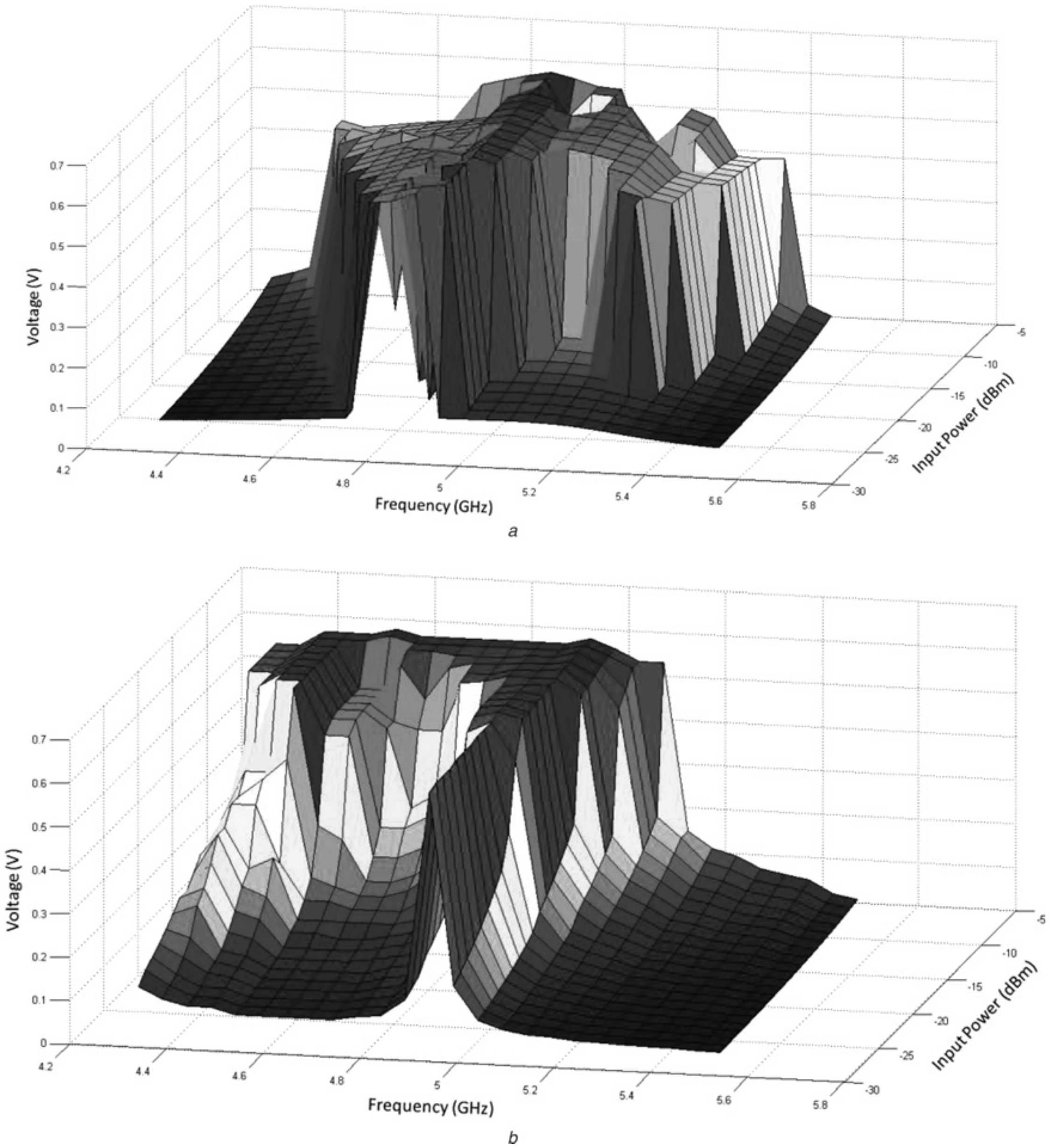

Fig. 8 *Injection-locked oscillator response for oscillator 1 against input RF signal frequency and power*

Freq. range from 4.3 to 5.5 GHz and P_{in} range from −27 to −5 dBm
a Simulations
b Measurements

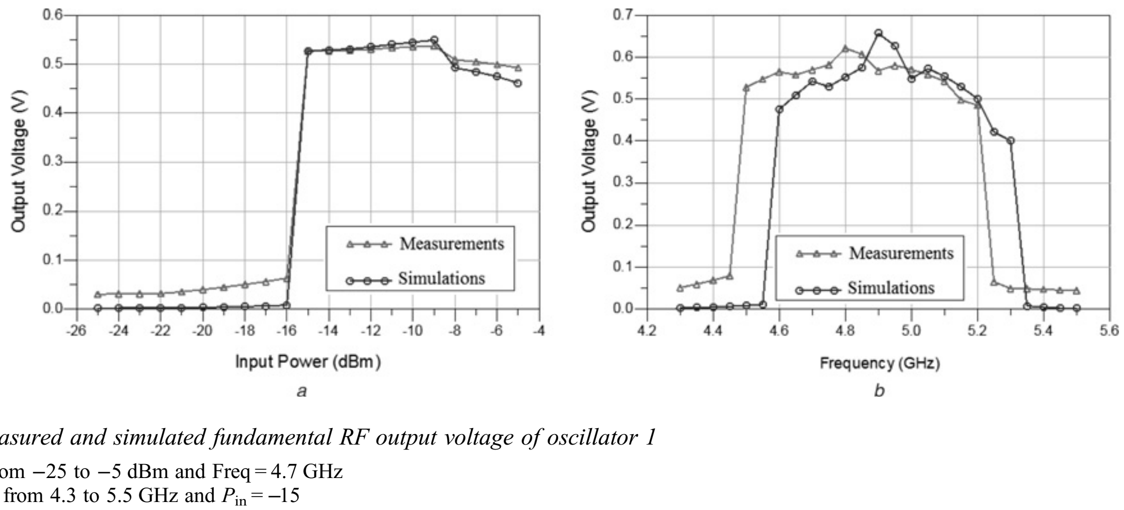

Fig. 9 *Measured and simulated fundamental RF output voltage of oscillator 1*

a P_{in} range from −25 to −5 dBm and Freq = 4.7 GHz
b Freq. range from 4.3 to 5.5 GHz and P_{in} = −15

doi: 10.1049/iet-map.2014.0118

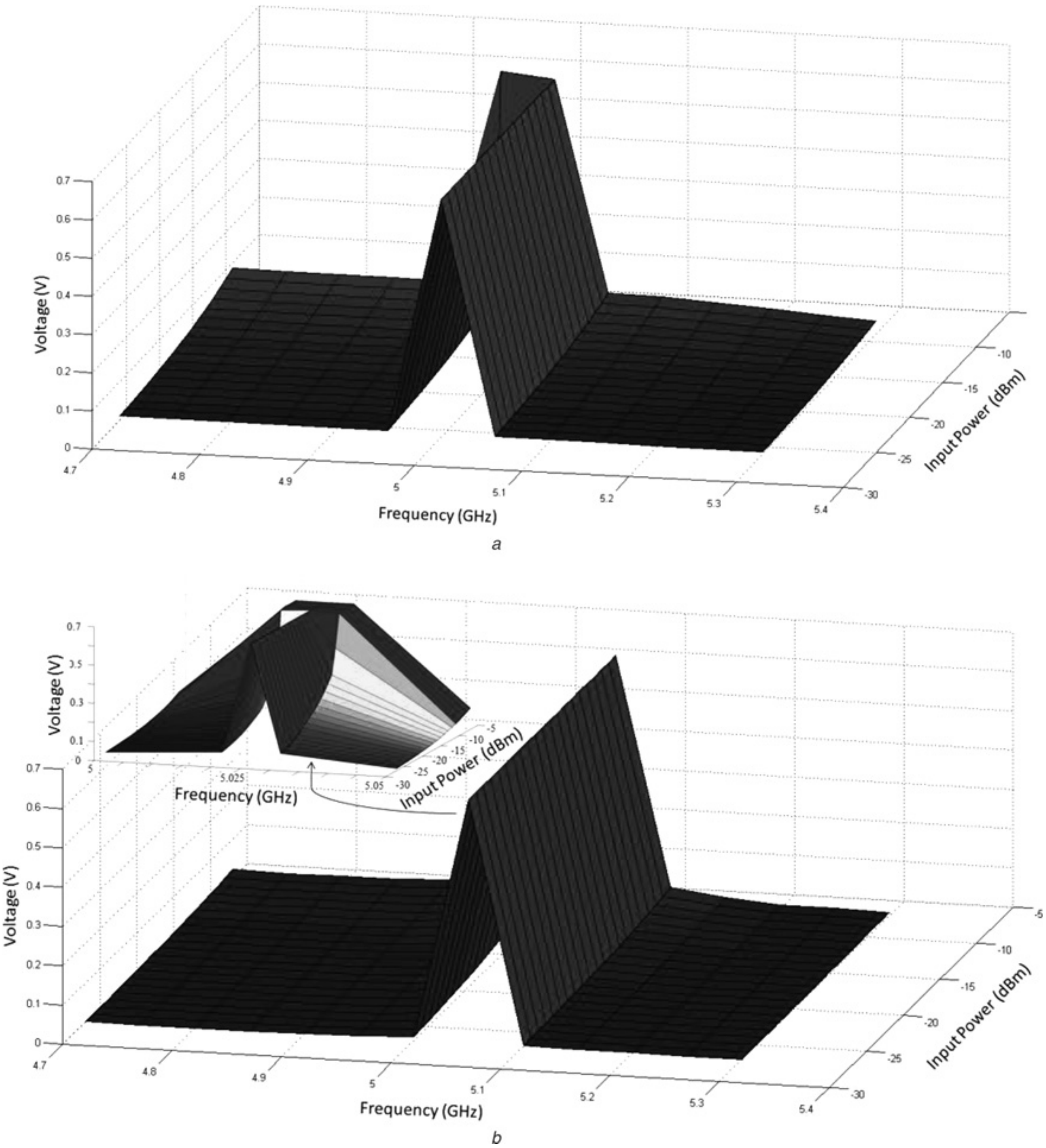

Fig. 10 *Injection-locked oscillator response for oscillator 2 against the input RF signal frequency and power*

Freq. range from 4.7 to 5.3 GHz and P_{in} range from −27 to −7 dBm
a Simulations
b Measurements, showing also a zoom between 5 and 5.05 GHz

figures, the X-parameters model is correctly predicting the measured behaviour of the injection-locked oscillator prototypes, thus demonstrating the usefulness of the proposed design methodology based on a behavioural model.

Finally, the measured RF output power at the fundamental, second and third harmonics of the synchronised oscillator 1, against power of the input synchronisation source at two different synchronisation frequencies can be seen in Fig. 11. In Fig 11*a*, the synchronisation frequency (Freq. = 4.95 GHz) is very close to the free-running frequency and the measured spectrum at low input power (P_{in} = −40 dBm) coincides with the oscillator in free-running conditions. In Fig. 11*b*, the synchronisation frequency is 200 MHz below than the free-running frequency, and injection locking phenomenon occurs from − 13 dBm. These measurements have been performed using the Maury-NMDG LSNA.

5 Conclusion

In this work, injection-locked oscillators have been designed, for the first time, using an X-parameters-based HBT model and a new measurement-based design methodology targeting high-power and high-synchronisation bandwidth. The behavioural model was extracted from LSNA load-pull measurements using a search iterative measurement-based procedure which also aided in determining the appropriate design output impedance space. To validate the proposed methodology, measurements of two injection-locked oscillator prototypes, optimised for different design goals (free-running and synchronised modes of operation), have been compared with simulations with the behavioural model. Satisfactory results have been obtained both in free-running and synchronised oscillation conditions.

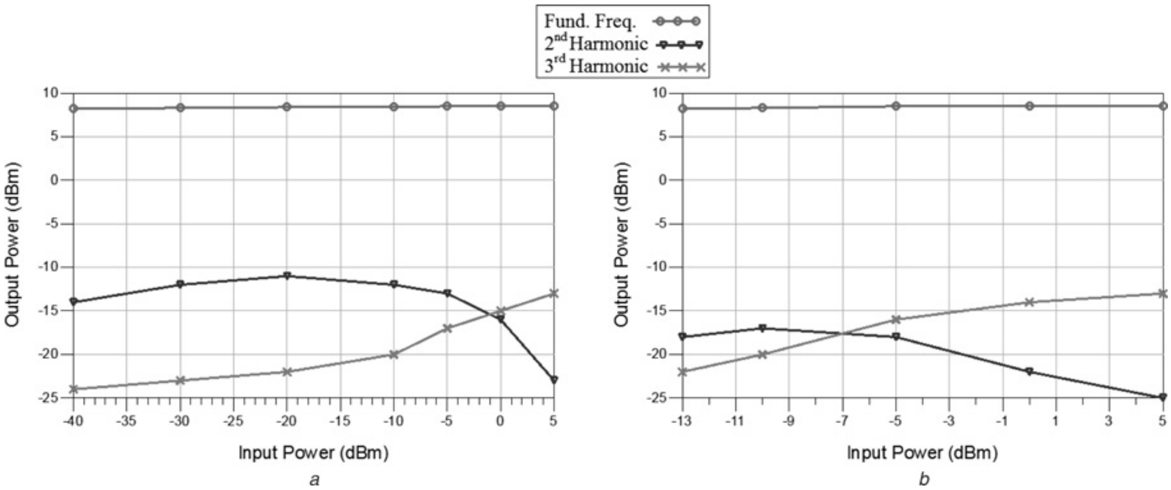

Fig. 11 *Measured RF output power at the fundamental, second and third harmonics of the synchronised oscillator 1 against power of the input synchronisation source*

a Fund. Freq = 4.95 GHz, close to free-running oscillation frequency
b Fund. Freq. = 4.75 GHz

6 Acknowledgments

Research supported by the Spanish National Board of Scientific and Technology Research, under project TEC2011-29264-C03-03, and the European Regional Development Fund (ERDF) and the Galician Regional Government under project CN 2012/260 ‘Consolidation of Research Units: AtlantTIC’.

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doi: 10.1049/iet-map.2014.0118