"AN INVESTIGATION OF A CASCADED PAIR OF INJECTION-LOCKED OSCILLATORS AT 2GHZ"

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ABSTRACT.

In EFTF 2001 an extension of Leeson's model for an oscillator was used to describe and demonstrate the properties of injection-locked oscillators, at 10MHz and 2GHz [1]. An explanation of the characteristic spectrum shape of a partially locked oscillator was also put forward Some further comments on this are included here.

In this paper, Leeson's model is used to describe the behaviour of a cascaded pair of injection locked oscillators operating at the same frequency of about 2GHz. The oscillators this time are single ended and not the 'balanced' configuration used previously at 2GHz. One oscillator is injected with a lower sub-harmonic frequency and this one provides an injection signal for the second oscillator. The objective is to obtain good suppression of the unwanted harmonics of sub-harmonic injection frequencies.

Measurements of the lock in range and capture range are compared with the theoretical predictions. Also measured and compared with theory is the suppression of the unwanted harmonics of the injection frequencies.

INTRODUCTION AND OVERVIEW

In EFTF 2001 an extension of Leeson's model [2] for an oscillator was used to describe and demonstrate the properties of injection-locked oscillators, at 10MHz and 2GHz [1]. We then put forward an explanation for the characteristic spectrum of a partially-locked oscillator, shown in Fig. 1 and also previously noted by Banai and Farzaneh [3].. The explanation was based on Leeson's model and was found to provide a simpler explanation than could be derived from the original injection locking models [4, 5]. In the next section of this paper our new explanation is summarised.

In this explanation we point out that injection locking *increases* the closed loop bandwidth of the tuned circuit from the very narrow value (of the order of mHz) that holds when self-oscillation is occurring, to a much larger value depending on the ratio of injection power to oscillator power. Although the bandwidth is much increased the oscillator still retains some ability to filter the spectrum of the injection signal.

The main purpose of this paper is to demonstrate the limitations of this filtering action. The filtering ability is found not to be very large and so we have measured a cascaded pair of oscillators so that the usefulness of the double filtering action that then occurs may be assessed.

The need for injection locking is often to select the harmonic of a lower frequency injected into the oscillator. The harmonic may already present in the injected signal or it may be generated in the oscillator itself. We have therefore also measured and compared the lock-in range and capture ranges for sine-wave injection at the fundamental frequency f_0 and for the sub-harmonics at $f_0/2$ and at $f_0/3$.

We have performed a further test on the filtering action of the injection locked oscillator. The injection signal was FM modulated so that a comparison of input and output spectra could show what filtering bandwidth could be achieved as the injection power was decreased.

INJECTION LOCKING BASED ON LEESON'S MODEL

Leeson's model with an input for the injection locking input is shown in Fig. 1.

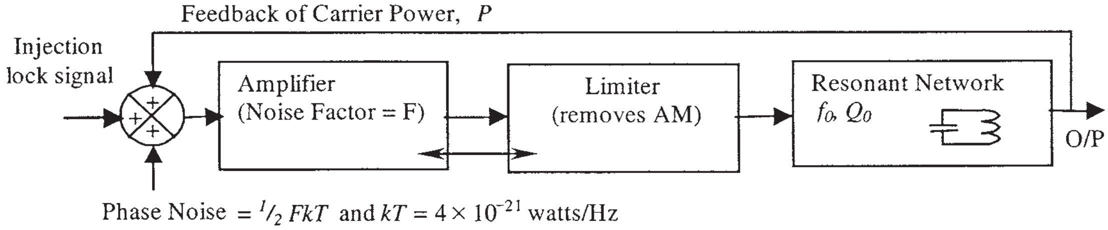

Fig1. Fundamental model of an oscillator (after Leeson) with injection locking input.

Fig. 2 shows the characteristic spectrum of a partially locked oscillator.

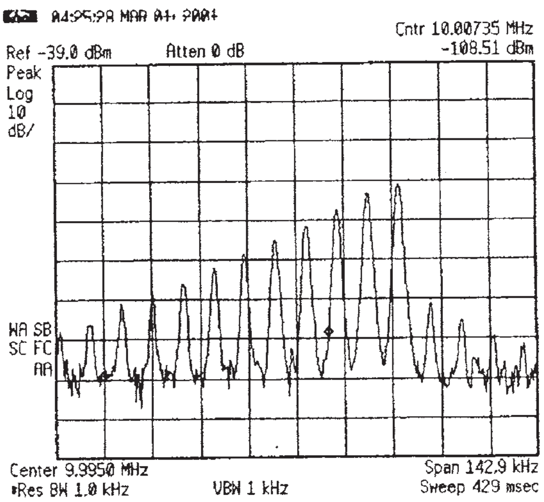

Fig. 2 Characteristic spectrum of partially-locked oscillator (at 10MHz)

The explanation of the partially locked spectrum is based on the generation of intermodulation products (IMPs) and the filtering of these by the closed loop transfer function of the tuned circuit

The power of each IMP is proportional to a fixed number, less than unity, to the power of the order of the IMP. The IMPs are equally spaced in frequency and the frequency offset of an IMP is proportional to its IMP order. Partial-locking means that the locking frequency is off-set from the tuned circuit resonator frequency and so the IMPs not falling into the tuned circuit pass-band are filtered out and this occurs on one side only of the locking frequency. The feedback gain of the oscillator is reduced by the power of the injection signal and so the pass-band is essentially flat over a substantial portion of the tuned circuit natural bandwidth and can cover many IMPs on one side of the injection frequency. When observed with a spectrum analyser with the usual log amplitude versus linear frequency scales the pass band IMPs are then on a straight line as shown in Fig. 2 This is because log of a power is proportional to that power. That is:

$$\log a^n = n \log a. \qquad (1)$$

THE INJECTION LOCKED OSCILLATORS

The block diagram of the 2 GHz cascaded oscillator pair is shown in Fig. 3. Note that a -20dB directional coupler is used to minimise injection backward from the second oscillator to the first oscillator.

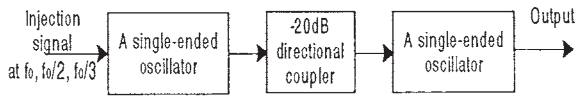

Fig. 3 Block diagram of a cascaded oscillator pair

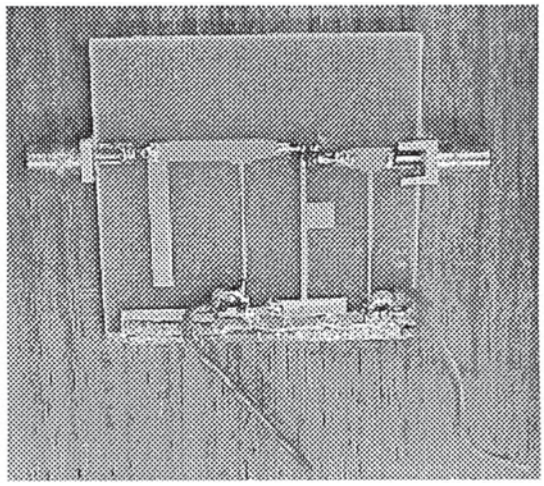

Fig. 4 2GHz oscillator board

Fig. 4 shows the one of the two identical single-ended oscillators used in the cascaded oscillator arrangement of Fig. 3. The single-ended oscillators are fabricated on FR4 board.

The Siemens CFY30 MESFET is used as the active device in each of the oscillators. The two-port negative resistance technique is used and the series feedback is connected to the source in order to meet the oscillation condition. This can be seen in the annotated layout of Fig. 5.

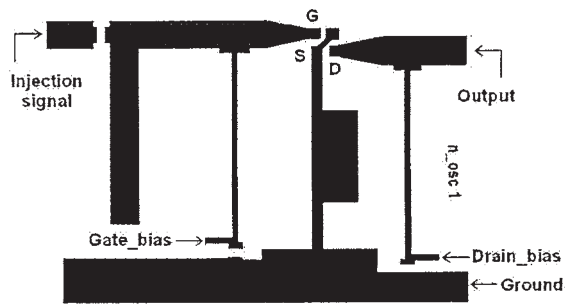

Fig. 5 Layout of 2GHz Oscillator Boards

MEASUREMENTS AND RESULTS

Spectrum Measurements:

Fig. 6 shows the free-running oscillator spectrum of the cascade oscillator with no injection signal. Although only just visible on the spectrum, the oscillator actually displayed considerable drift and environmentally induced FM.

The cascade oscillator was deliberately not screened for any of the tests so that higher levels of injection locking had to be applied to ensure stabilisation

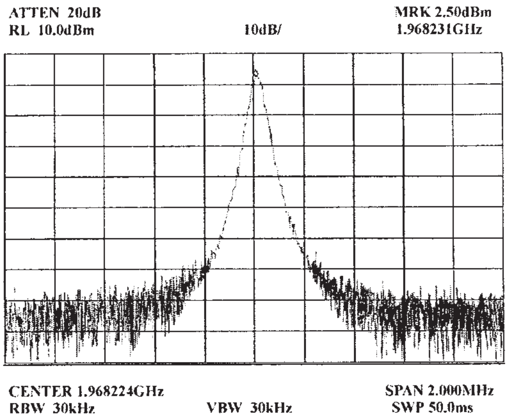

Fig. 6 Free-running cascade oscillator output spectrum (with no injection signal).

Figs 7a and 7b compare the output spectra of the first and second oscillators in the cascade circuit at the three injection frequencies, $f_0/3$, $f_0/2$ and f_0. Although different injection power levels were tried the figures show no spectral improvement from the second oscillator (in the rgion of the spectrum shown). This was a disappointing result.

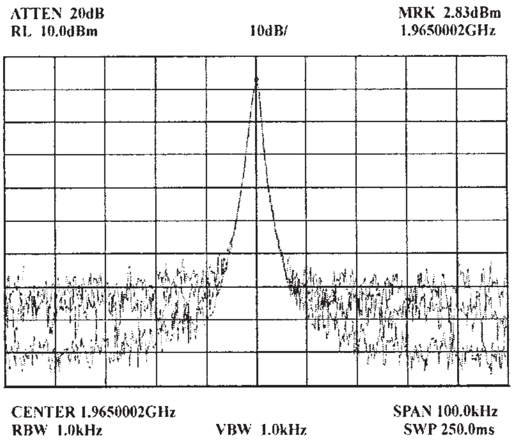

Fig 7a. Output of the *first* injection locked single-ended oscillator for $f_0/3$, $f_0/2$ and f_0 injection frequencies and at different injection power levels

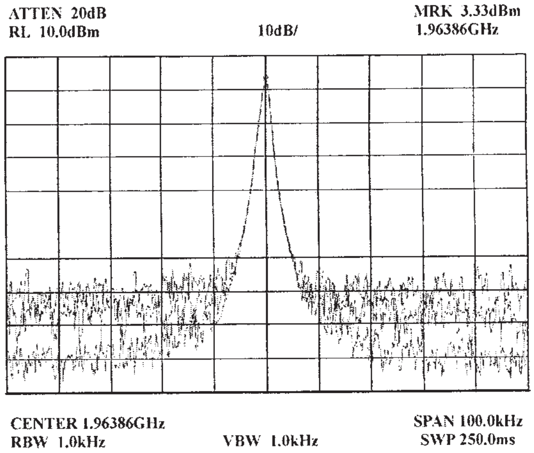

Fig 7b. Output of the *second* injection locked single-ended oscillator for $f_0/3$, $f_0/2$ and f_0 injection frequencies and at different injection power levels,

Figs 8a and 8b compare the output spectra of the first and second oscillators in the cascade circuit with an injection frequency of $f_0/3$. A wide span was selected so that the unwanted sub-harnonics at $f_0/3$,$2f_0/3$, $4f_0/3$, and $5f_0/3$ can be seen. Fig. 8b shows a 20dB reduction in the unwanted components. Thus in this case the second oscillator is giving a worthwhile improvement.

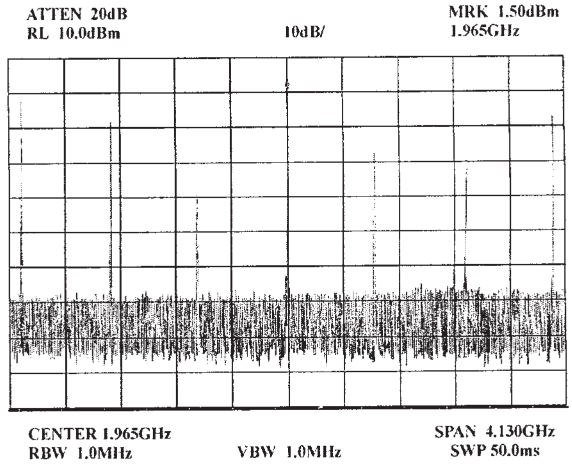

Fig 8a. Output of the *first* injection locked single-ended oscillator for $f_0/3$ injection frequency.

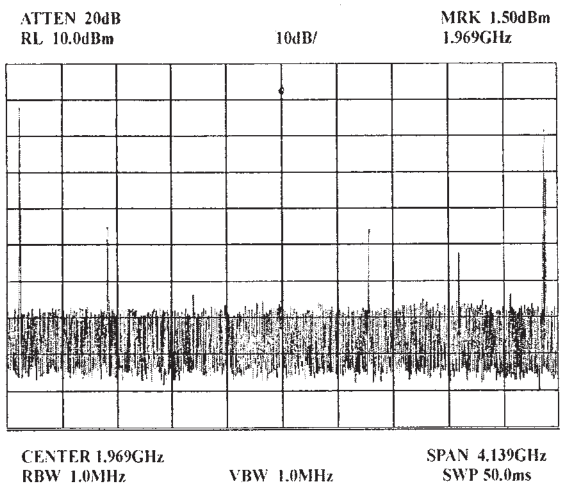

Fig 8b. Output of the *second* injection locked single-ended oscillator for $f_0/3$ injection frequency

Figs 9a and 9b compare the output spectra of the first and second oscillators in the cascade circuit with an injection frequency of $f_0/2$. A wide span was selected so that the unwanted sub-harmonics at $f_0/2$, and $3f_0/2$ can be seen. Fig. 9b also shows a 20dB reduction in the unwanted components. Again the second oscillator is giving a worthwhile improvement of 20dB.

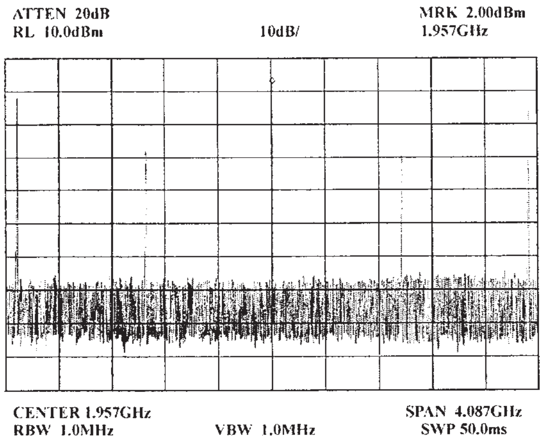

Fig 9a. Output of the *first* injection locked single-ended oscillator for $f_0/2$ injection frequency

In order to optimise the suppression of close-to-carrier spurious signals the injection signal must be kept as low as possible. As already mentioned, a high-level injection signal reduces the oscillator loop gain and this considerably increases the oscillator closed loop bandwidth so that it cannot filter out close-in signals to the same degree.

If the natural bandwidth of the resonator is f_{BWres} , the closed loop filtering bandwidth f_{BWcl} for injection power P_i and oscillator power P_{OSC} will be given approximately by:

$$f_{BWcl} = f_{BWres} \, (P_i / P_{OSC})^{0.5} \qquad (2)$$

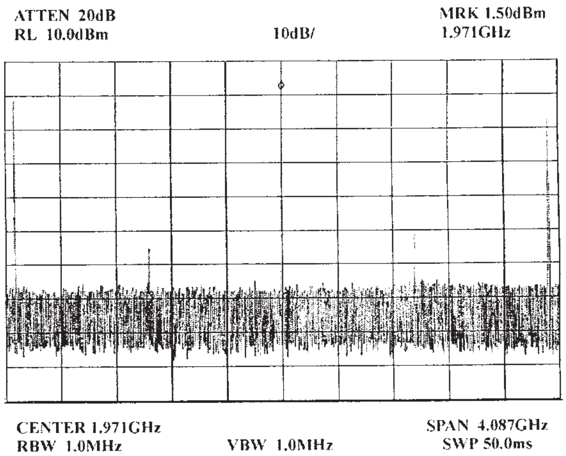

Fig 9b. Output of the *second* injection locked single-ended oscillator for $f_0/2$ injection frequency

Fig. 10a shows the spectrum of an FM signal with a modulation frequency of 50kHz that we have used to optimise the close-in suppression. Fig. 10b shows that with an injection locking level of –15dBm essentially there is no suppression of the 50kHz sidebands. However when the injection level is lowered to –20dBm about 7 dB of suppression is achieved.

At the –20dBm level the oscillator was only just locked because of the high level of residual FM that the cascade oscillator had in its free running state.

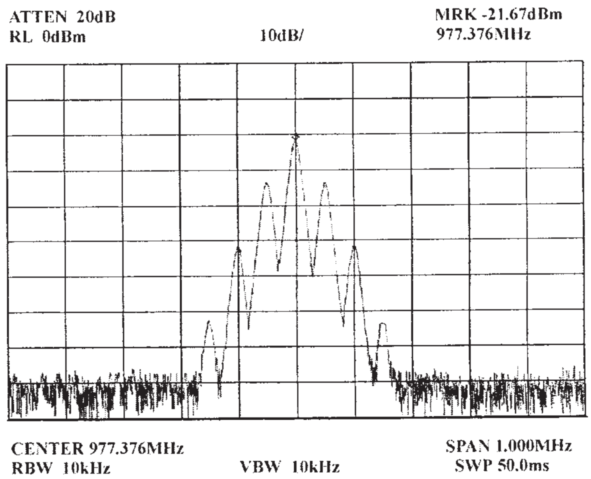

Fig. 10a The FM input injection signal to the cascaded oscillator power.

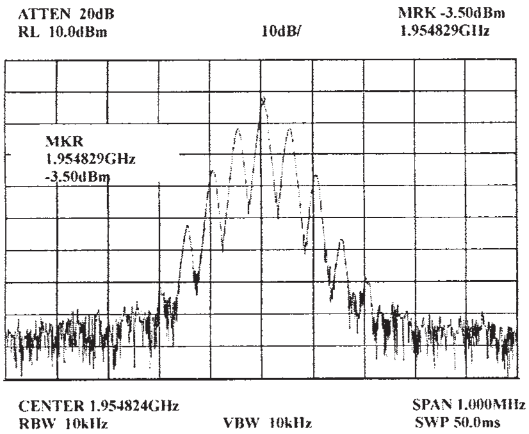

Fig 10b. The output spectrum of the cascaded oscillator when locked to the injection FM input at $f_0/2$ with a power level of -15dBm.

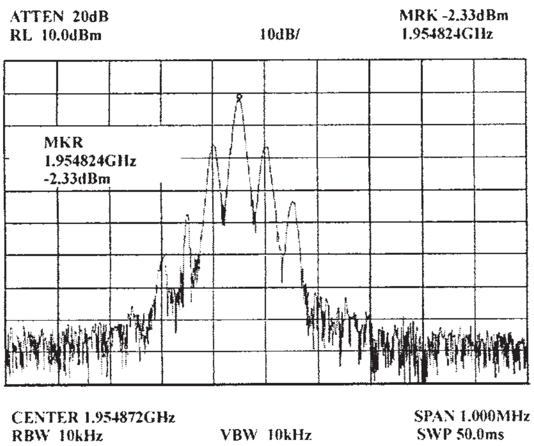

Fig 10c. The output spectrum of the cascaded oscillator when locked to the injection FM input at $f_0/2$ with a power level of –20dBm.

Capture and Lock-in Range Measurements:

Tables 1 and 2 show the capture and lock-in ranges at different injection power levels for injection frequencies respectively at $f_0/2$ and $f_0/3$. The results at $f_0/2$ and $f_0/3$ in both cases show the two-to-one ratio between the lock-in and capture ranges previously found for the balanced 2GHz oscillator dicussed in our previous paper [1].

Table 1: Injection frequency at $f_0/2$ with cascade configuration.

Input power level (dBm)	Capture range (kHz)	Lock-in range (kHz)
-8	353.1	630.8
-10	214.4	460.2
-12	124.4	251.0
-14	74.8	151.1
-16	36.9	71.3

Table 2: Injection frequency at $f_0/3$ with cascade configuration.

Input power level (dBm)	Capture range (kHz)	Lock-in range (kHz)
-4	43.57	84.12
-6	28.11	42.47
-8	22.90	36.80
-10	16.90	32.23
-12	12.10	21.2

The tables also show that a much higher level of injection is required at $f_0/3$ to achieve the same capture and lock-in ranges as for $f_0/2$.

MAIN CONCLUSIONS.

The Leeson oscillator model can be used, at least qualitatively, to explain the main characteristics of sub-harmonic injection locking.

The previously predicted two-to-one ratio between the lock-in and capture ranges also holds for sub-harmonic injection locking.

A cascade pair of injection locked oscillators gives a useful extra suppression of the unwanted harmonics of a sub-harmonic injection frequency.

Good close-in noise can only be achieved with low levels of injection and therefore with small capture and lock-in ranges. Also the oscillator must then have a good stability when free-running.

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