Reduced Flicker Noise in Microwave Oscillators using Feedforward Amplifiers

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***Abstract* — Transposed flicker noise removal is demonstrated in a 7.6GHz microwave oscillator for offsets greater that 10kHz. This is achieved by using a GaAs based feedforward power amplifier as the oscillation sustaining stage. 20dB noise suppression is demonstrated at 12.5kHz offset when the error correcting amplifier is switched on. The phase noise rolls-off at $(1/\Delta F)^2$ for offsets greater than 10kHz and is therefore set by the thermal noise to within 0-2dB of the theoretical minimum.**

I. Introduction

Oscillators built at microwave frequencies, using GaAs devices, usually offer greatly degraded phase noise performance due to transposed flicker noise. This is typically 20-30dB worse than their silicon counterparts, at offsets around 10kHz.

The main techniques used to reduce this can be summarized under the following headings.

1. RF detection and LF cancellation [1],[2],[3],[4],[15]
2. Direct LF reduction [5],[6],[7]
3. Transposed Gain Amplifiers [8],[9],[10]

1: Z. Galani, M.J. Bianchini, R.C. Waterman, R. Dibiase, R.W. Laton and J.B. Cole [1] detected the phase noise by using a two port resonator as both the oscillator resonator and as a one port discriminator. The signal from the discriminator was then used to apply cancellation to a separate phase modulator within the loop. A 20dB suppression of close to carrier noise was reported at 10kHz offset from a 10GHz carrier. Most recently E.N. Ivanov, M.E. Tobar and R.A. Woode [2],[4] have produced some of the lowest noise room temperature X-band oscillators using sapphire whispering gallery mode dielectric resonators and sophisticated error correction circuits.

2: A.N. Riddle and R.J. Trew [5] designed a feedback amplifier using a pair of FETs operating in push pull at microwave frequencies but operating in parallel at low frequencies via a low frequency connection between the two bias networks. Rohde and Newkirk describe some new oscillators using low frequency feedback which demonstrate very good results [15].

3: J.K.A. Everard and M.A. Page-Jones [8],[9], and M.M. Driscoll and R.W. Weinert [10] developed independently the transposed gain amplifier. A technique where by low frequency gain can be transposed up to microwave frequencies through the use of silicon based mixers and a silicon based LF amplifier. The system proposed by Everard and Page-Jones also included a delay line in between the two LO paths to ensure negligible phase noise degradation from the LO. This enables the use of an LO with poor phase noise. A flicker noise corner of between 1-3kHz has been reported.

Recently Broomfield and Everard presented reduced flicker noise transposition in a 1-Watt feedforward amplifier at the IEEE 2000 Frequency Control Symposium [11]. In [11] it was shown that the feedforward technique could be used to reduce the transposed flicker noise (in an amplifier) in a manner similar to the way it reduces distortion and conventional thermal noise. This was demonstrated in [11] using phase and amplitude characterisation of the amplifier. This is extended here to demonstrate flicker noise suppression in oscillators.

II. The Feedforward Amplifier

A simplified feedforward amplifier is shown in fig. 1. G is the amplifier gain, K_1 is the coupler ratio. The main path without error correction goes from A to B. The error signal is derived from the left hand loop AC – AD. The error correction is then obtained from the upper path and the right hand loop AB – EB.

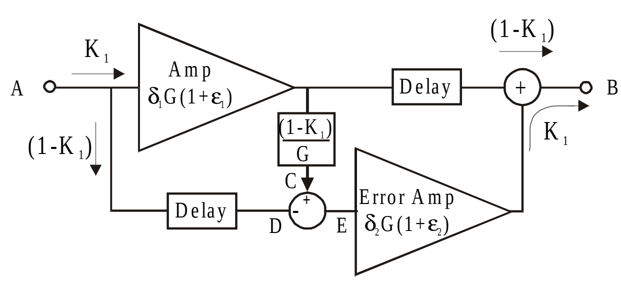

Fig. 1. Feedforward amplifier topology

Flicker noise is modulation noise which means that the ratio of sideband noise to carrier level is constant. Therefore the absolute level of the sideband noise varies with carrier level. Experimental measurements of flicker noise are described in [16].

A phasor analysis is performed in [11], however a simplified analysis is performed here. The flicker noise of the main amplifier is represented as $(1+\varepsilon_1)$ and the error correcting amplifier as $(1+\varepsilon_2)$. The amplifier balance is represented as δ_1 and δ_2. Note that perfect balance occurs when $\delta = 1$ therefore the suppression of each loop in decibels = $10\log(1-\delta)$. The power transfer function of the amplifier shown in fig. 1 is therefore:

$$P_T = K_1 G(1-K_1)\begin{bmatrix}\delta_1\varepsilon_1(1-\delta_2)+\delta_2\varepsilon_2(1-\delta_1)-\delta_1\delta_2\varepsilon_1\varepsilon_2 \\ +\ (\delta_1-\delta_1\delta_2+\delta_2)\end{bmatrix} \quad (1)$$

where $K_1G(1\text{-}K_1)$ is the ideal amplifier gain. Assuming that δ_1 and δ_2 are close to one (of order 0.1% to 1%) and ε is very small then this equation simplifies to:

$$P_T = K_1 G(1-K_1)[1+\varepsilon_1(1-\delta_2)+\varepsilon_2(1-\delta_1)] \quad (2)$$

If each loop suppression is assumed to be 23dB and the flicker noise levels of each amplifier the same then a flicker noise suppression of 20dB can be obtained. Of course the total noise cannot be suppressed below the noise figure of the feedforward amplifier.

II. Noise Figure Analysis

In feedforward amplifiers, all noise components originating from the main amplifier are suppressed and the noise figure of the system is set by the noise produced in the error correcting amplifier and the losses in that signal path, as shown in equation (3). The noise figure for our topology is 11.5dB.

$$F_{ff} = \frac{F_{error}}{L_{input\ coupler}\,L_{delay\ line}\ L_{error\ amp\ input\ coupler}} \quad (3)$$

III. Amplifier Gain Requirements

From oscillator phase noise analysis [12], [17] it can be shown that if the system phase noise is thermal noise limited, the overall single sideband phase noise of the oscillator can be expressed as:

$$L_{fm} = \frac{FkT}{8Q_0^{\,2}\left(\frac{Q_L}{Q_0}\right)^2\left(1-\frac{Q_L}{Q_0}\right)^2 P_{avo}}\left(\frac{f_0}{\Delta f}\right)^2 \quad (4)$$

Where F = The amplifier noise figure, k = Boltzmann constant, T = Temperature, Q_0 = The unloaded Q of the resonator, Q_L = The loaded Q of the resonator, P_{avo} = The power available from the output of the amplifier, f_0 = The centre frequency and Δf = The carrier offset frequency. The noise performance is therefore minimum when Q_L/Q_0 = ½ and the amplifier gain is 4 (6 dB). Excluding coupler losses and assuming K_1 = ½ the ideal amplifier gain should therefore be 16 (12dB). To allow for other losses 15dB was chosen.

IV. Amplifier Realisation

A 1-Watt feedforward power amplifier that operates over a ±250MHz bandwidth at 7.6GHz has been designed and built [11]. This system utilised two commercially available multistage GaAs based amplifiers, both with gains of 15dB and a P_{1dB} of +35dBm for the main amplifier and a P_{1dB} of +28dBm for the error-correcting amplifier. The directional couplers, hybrid combiners, power dividers, attenuators and delay lines have all been designed and produced in house. The signal loops are balanced by allowing the amplifiers to reach a quasi-stable temperature state and adjusting both phase and amplitude within the loops, for maximum cancellation.

V. Residual Flicker Noise Measurement

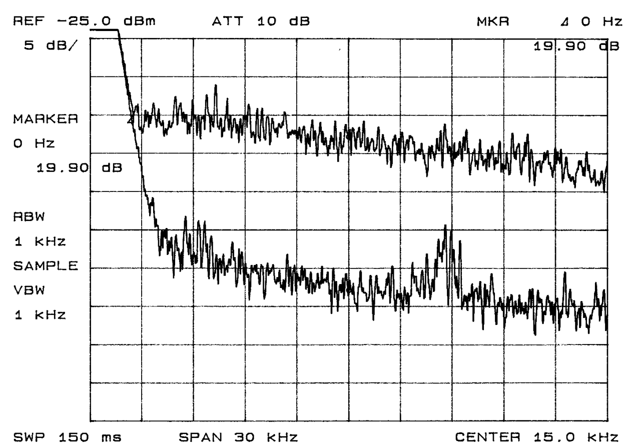

Fig. 2. Residual flicker noise measurement, upper trace; error correcting amplifier switched off, lower trace; error correcting amplifier switched on. This shows ~20dB suppression over the measured bandwidth of 1-30kHz.

The residual flicker noise of the amplifier was measured using a delay line frequency discriminator and a reduction in residual phase noise level of approximately 20 dB was observed (fig. 2).

The flicker noise level below the carrier was calculated to be less than –150dBc/Hz @10kHz offset when the error correcting amplifier was switched on.

VI. THE FEEDFORWARD OSCILLATOR

The feedforward amplifier can be used as the oscillation sustaining stage in a low noise oscillator [13], [14]. However the amplifier must not be allowed to saturate as this will affect the loop balance and effectiveness of the amplifier to suppress flicker noise. An oscillator is therefore produced with the addition of a resonator, an output coupler, a phase shifter and a limiter, as shown in fig. 3.

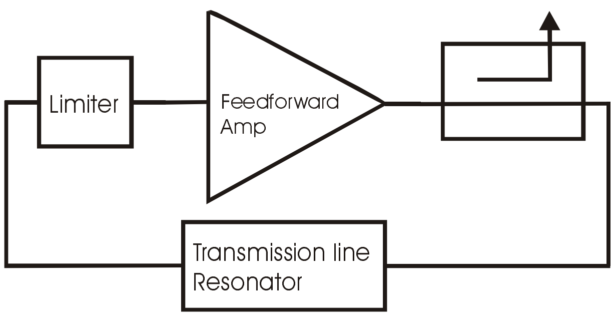

Fig. 3. Schematic diagram of the feedforward oscillator

A 7.6GHz transmission line resonator was designed with 2.5dB insertion loss and a loaded Q of 45, (Q_0~180), a 10dB output coupler and a silicon diode limiter with a threshold level of +9dBm. A typical phase noise plot can be seen in fig. 4 and a phase noise comparison between the oscillator with the error correction on, and error correction off, is shown in table 1. The reduced value of Q_L/Q_0 was required to account for the losses of the limiter and loop components.

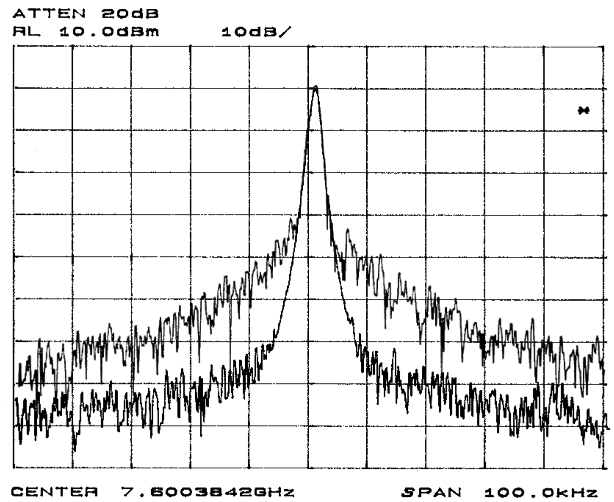

Fig. 4. Phase noise measurement, upper trace; error correction off, lower trace; error correction on.

TABLE I

A COMPARISON OF SINGLE SIDEBAND PHASE NOISE WHEN THE ERROR CORRECTING AMP IS SWITCHED ON AND OFF

Single side band phase noise level, L (dBc/Hz)			
Offset from carrier	Error amp OFF	Error amp ON	Theory
12.5kHz	-79.8	-100.3	-102.5
25kHz	-88.5	-107.5	-108.5
50kHz	-98.6	-114.4	-114.5
100kHz	-107.2	-120.8	-120.5

Assuming the noise figure of the feedforward amplifier is 11.5 dB (1.3dB for limiter, 5dB loss for couplers and delay line and 5.2dB for error amplifier – all measured), P_{avo} = +16dBm and Q_L/Q_0=1/4 then L_{fm} = -107.5dBc/Hz at 25kHz offset which is within 1 dB of the theory. It should be noted that the close to carrier phase noise approximately follows a $1/f^3$ law when the error correction is switched off, and a $1/f^2$ law when the error correction is switched on.

VI. CONCLUSIONS

A GaAs based feedforward amplifier operating at 7.6GHz has been analysed, designed, and produced. Residual flicker noise suppression of 20dB at carrier offsets between 1-30kHz was achieved. A low phase noise oscillator incorporating this feedforward amplifier is shown to demonstrate close to carrier phase noise reduction of 20dB at 12.5kHz offset. The phase noise performance, in the thermal noise region, is within 1dB of the theoretical minimum.

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