

Experimental Study on MOSFET's Flicker Noise under Switching Conditions and Modelling in RF Applications

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Abstract

The flicker noise mechanism under switching conditions is studied. Experimental results show that the baseband flicker noise is a superposition of upconverted gate flicker noise at each harmonic of the output current. Methods to reduce the flicker noise are discussed. Based on the measured results, the large signal flicker noise model for RF applications under switching conditions is proposed and validated by simulations and measurements. With the proposed model, the noise performance of a single-balanced gilbert mixer for direct conversion applications is analysed and discussed.

I. INTRODUCTION

CMOS technology has received much attention due to its process simplicity, low cost and high integration. However, the flicker noise associated with MOS devices is much more severe than that with bipolar technology, which has a profound effect on analog integrated circuits, especially for narrow band direct conversion receivers [1]. It not only degrades the noise performance of mixers and phase noise of oscillators, but also adds noise directly to the base band.

In RF applications, the transistors often move rapidly from one operating region to another. In an ordinary mixer or an oscillator, the transistors go from the off state to the saturation region or linear region. The effect of $1/f$ noise in these rapidly changing environments is rarely reported [2, 3]. Gierkink [2] has observed the differences between static DC conditions and switching conditions and utilized it to improve the noise performance of the circuit. But the property and mechanism of flicker noise under switching conditions have not been deeply studied. Darabi [3] analyzed the switching case from the linear region to the off state theoretically and gave a simple model. However, an understanding of noise under other switching transitions is still necessary.

In this paper, we focus on the characteristics, the model, and the impact of $1/f$ noise under switching conditions. The measurement setup is given in the following section. Section III describes the methodology to analyze the noise spectrum and shows the measurement results. Methods to reduce the flicker noise are discussed also. The flicker noise model is then proposed in section IV. It is validated by simulations and measurements. An RF application using the model is

demonstrated in section V and finally a conclusion is drawn.

II. MEASUREMENT SETUP

To study the correlated flicker noise in a nonlinear environment, measurement is done with a setup as shown in Fig. 1. Well-matched differential transistors with their gates connected together were fabricated in the TSMC0.35 μ process. Note that the circuit and spectrum analyzer are differential. This eliminates the uncertainty and common-mode noise of the input signal that are usually associated with a single-ended test setup. Variable resistors are used to compensate for the device mismatch and to suppress the common mode signal and noise generated by the function generator. Their values are chosen to ensure proper transistor operation region and sufficient bandwidth for differential output. A low frequency differential dynamic signal analyzer SR780 with very high frequency resolution and low noise floor is used to analyze the noise spectrum.

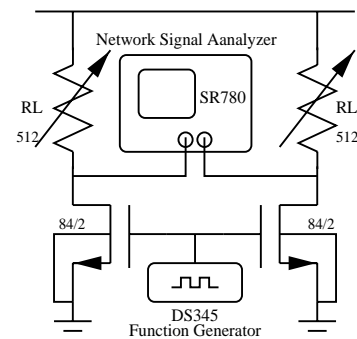


Figure 1 Measurement setup of flicker noise under switching conditions. (NMOS: $V_{th}=0.6V$ TSMC0.35 μ 3M2P)

III. SPECTRUM ANALYSIS

Darabi [3] has asserted that the baseband flicker noise at the mixer output is independent of the switching frequency, assuming that enough output bandwidth is given. The assertion is verified with the measurement in Fig. 2. As a result, we use a quiet and versatile generated waveform at the input to simulate the effect of switching at a higher frequency. The method to analyze the flicker noise spectrum under switching is illustrated by switching from the off region to the saturation region with a square wave input. Such switching is the usual case for mixers and oscillators.

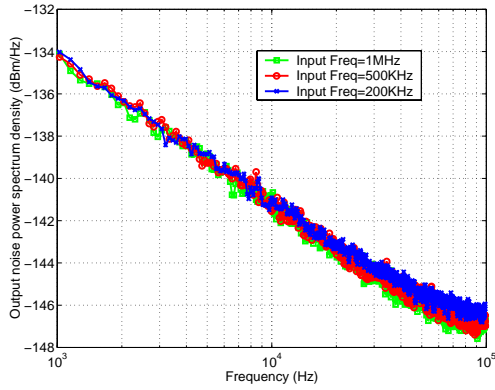


Figure 2 Baseband noise under fast switching. Input: Square Wave VGS=0.6V VPK=0.5V (OFF-SAT).

While earlier studies have postulated that the correlated flicker noise could not respond to switching, Fig. 3 shows that there are large noise peaks at the harmonics. A superposition of flicker noise at each harmonic component of the output current is seen. At the lower frequency end, the noises under different switching frequencies converge. It is clear that the noise contributions from the DC harmonic are the same, which is consistent with the observation in Fig. 2. Based on the frequency independence property from the baseband flicker noise observed above, the noise contribution from the DC component of the current can be approximated by the noise under fast switching.

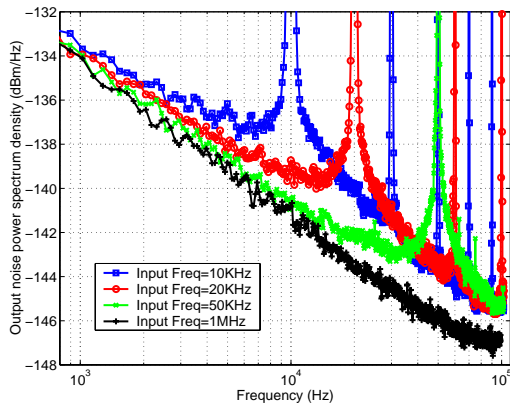


Figure 3 Baseband noise under slow switching. Input: Square Wave VGS=0.6V VPK=0.5V (OFF-SAT).

To study the relationship among noise harmonics, the flicker noise at DC is subtracted out and the noise spectrum is further processed by shifting the right-side band noise at the switching frequency to zero frequency, as plotted in Fig. 4. The spectrum under higher switching frequency is exactly parallel to that of the DC harmonic noise response. A conclusion that the output noise is a superposition of upconverted flicker noise at each harmonic component of the output current can be drawn. When the switching frequency is low, the noises at higher harmonics superposed at the side band so that we can not see the parallel relationship clearly.

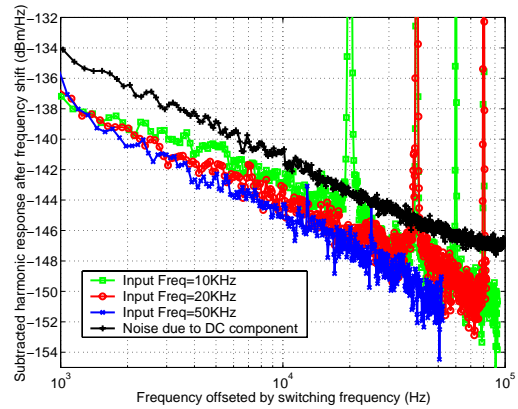


Figure 4 Single side band harmonic noise response compared to noise contribution from DC component.

Fig. 5. shows the measured baseband output noise with different transitions. The peak of static DC noise is the transition from the saturation (SAT) to the linear region (LIN). The baseband noise is close to static DC noise when the switching amplitude is small except LIN-OFF transition. OFF-SAT and OFF-LIN are often used in mixer and osc applications. SAT-SAT can be used in a specific mixer [4]. LIN-LIN and SAT-LIN may be used in current-mode circuits. The figure indicates that different transitions have different properties. For OFF-SAT and LIN-LIN, the larger the swing is, the larger is the output noise, which are different from OFF-LIN and SAT-LIN. In the case of OFF-SAT, the noise variation with the switching swing decreases with VGS. To reduce the output noise, small VGS and small swing should be chosen. When entering SAT-SAT, the output noise keeps almost constant, which is the same as static DC noise. LIN-OFF and SAT-LIN have the same tendency. The minimum output noise can be achieved by biasing VGS at the transition point from the saturation to the linear region with the largest switching swing. The conclusion is of significance to mixer baseband noise and oscillator phase noise. Experimental results also show that for LIN-OFF and SAT-OFF, if the on state voltage is fixed, lowering the off state voltage also reduces the noise.

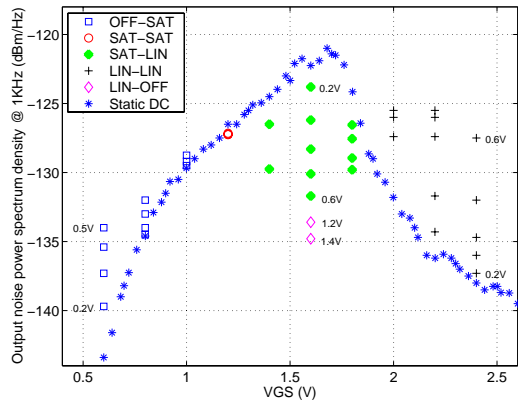


Figure 5 Measured baseband noise with different transitions. Volts indicated is switching swing VPK. Input: Sine Wave @ 1MHz.

The spectrum composition of the output noise under switching and different transitions was discussed. The measurement and analysis above are based on the fact that enough output bandwidth is ensured. However, the output bandwidth definitely influences the results because it affects the harmonic composition of the output current when it is smaller than the switching frequency. For down conversion mixers, the switching frequency is much larger than the output bandwidth. The output noise is dependent on the switching frequency. After tackling the non-linear process of flicker noise under switching, it is easy to study the effect of output bandwidth using the noise model described in the next section.

IV. FLICKER NOISE MODELLING

Based on the experimental results above, the flicker noise under switching can be modeled by amplitude modulation (AM) as shown in Fig. 6; where g_k is the voltage gain at each harmonic. However, it is found that the model can not be applied to LIN-OFF transition. LIN-OFF case can be modeled by pulse width modulation (PWM) due to its sharp edge and large swing. A formulation was given in [3]. Based on the proposed model, it is possible to calculate the noise level at the output of the nonlinear circuit. The method is to apply a small signal at the gate of the switching transistor, and simulate its gain at the harmonics of the switching frequency including DC. The total noise at the output is the superposition of upconverted noise at each harmonic.

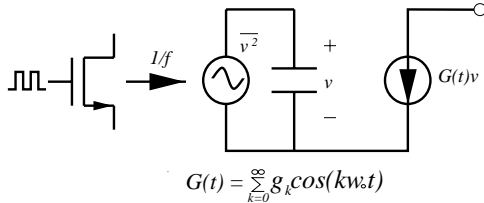


Figure 6 Flicker noise model under switching conditions except LIN-OFF. Where g_k is the voltage gain at each harmonic.

The model is verified by different switching waveforms through measurement and Hspice simulation. The comparison between the simulation and measurement results given in Table 1 indicates that the results agree well. The output noise depends on the signal feed-through gain g_0 rather than on the slope of the waveform. Different switching transitions are also verified in Fig. 7. The noise response at switching frequency is very small for both SAT-LIN and SAT-SAT. It increases very rapidly with switching amplitude for LIN-LIN transition while it is relatively large for OFF-SAT but not so sensitive to the swing.

Fig. 8 shows the difference between LIN-OFF and other transitions. As predicted in [3], the noise appears only at the even harmonics for LIN-OFF transitions while other transitions also have odd-harmonic noise components. The spectrum analysis verifies the formula given in [3] that the

noise response at double switching frequency is the same as the DC harmonic noise response.

Table 1: Model verification with different waveforms

Waveform	Normalized Gain @ DC (dB)	Measured relative baseband noise @ 1KHz (dB)	Simulated gain at switching frequency relative to gain @ DC (dB)	Measured harmonic noise relative to DC noise (dB)
Square	0	0	-3.9	-4
Sine	-2.6	-2.4	-2.7	-2.6
Triangular	-3.9	-4.1	-2.8	-3.1
Ramp	-4	-4.1	-3.3	-3.5

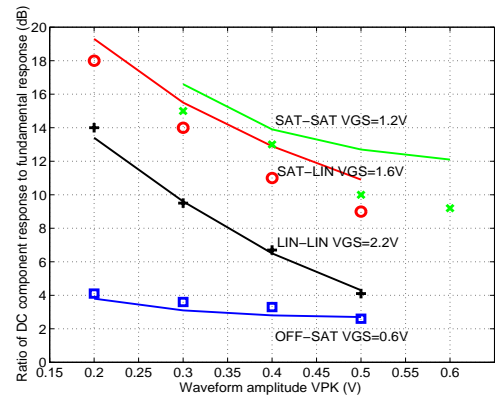


Figure 7 Model verification by different transitions. Solid line stands for simulation and symbols for measurements. Input: Sine Wave @ 1MHz.

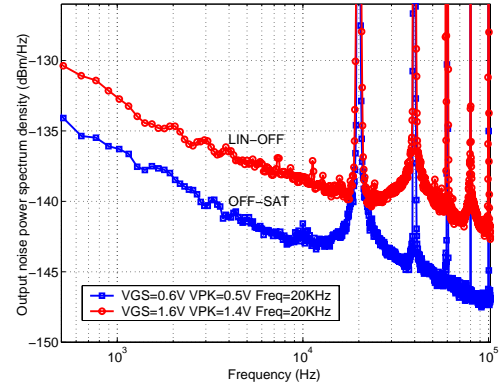


Figure 8 LIN-OFF transition has a different mechanism from other transitions.

V. AN RF APPLICATION

For direct-conversion receivers, the mixer is the key component for directly converting the RF signal to the baseband signal. The flicker noise at the same frequency band is usually a serious issue which dominates the noise spectrum and severely degrades the noise performance. Noise analysis and optimization are extremely necessary.

The single-balanced gilbert mixer is shown in Fig. 9. Its

noise performance is related to the total baseband noise at the output and the RF signal gain. To simplify, only the flicker noise is considered. The flicker noise at the RF transconductance stage will be upconverted and has no contribution at the baseband. Only switching transistors contribute flicker noise at the output. Therefore, the ratio of the flicker noise gain g_0 to the RF signal gain is the measure of the noise performance. The smaller the ratio is, the better is the noise performance. The flicker noise gain is measured from the LO input to the mixer output.

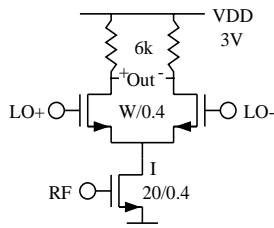


Figure 9 Single-balanced gilbert mixer

Firstly, the effect of the output bandwidth and switching frequency is studied. The transistors switch from the off state to the saturation region. The width of the switch transistor is used to change the output bandwidth and its effect on the input-referred flicker noise is not considered. As shown in Fig. 10, when the switching frequency is much less than the output bandwidth, the output flicker noise is frequency independent. It is consistent with what we observed previously. As the switching frequency increases, the output flicker noise gets larger and the signal gain becomes smaller. Subsequently the input-referred noise gets much larger. For better noise performance, higher output bandwidth or lower switching frequency is preferred.

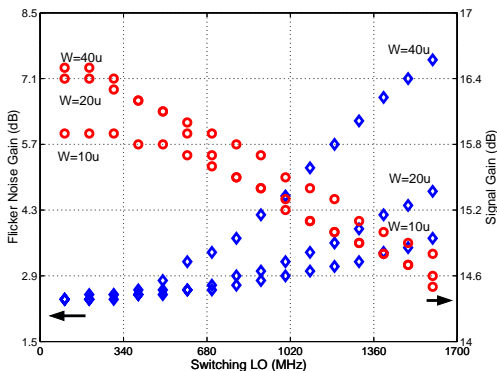


Figure 10 Effect of output bandwidth and switching frequency

The LO swing is another important factor for consideration. Fig. 11 shows that the larger the LO swing is, the better is the noise performance. In this case, the on-state gate voltage almost keeps constant due to the fixed biasing current. The off-state gate voltage of the switch decreases with the swing. As we mentioned before, to reduce flicker noise, a lower off-state gate voltage is needed. In other words, the

large LO swing improves the noise performance.

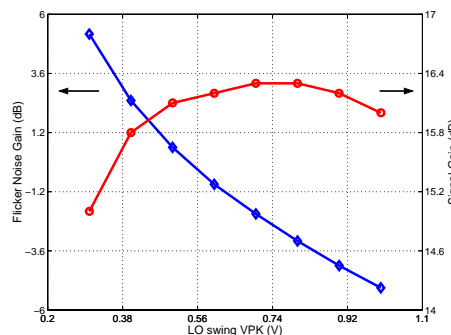


Figure 11 Effect of LO swing

The effect of the bias current of mixer is also studied. Both the flicker noise gain and RF signal gain increase with the bias current. However, the flicker noise gain increases more quickly. That means the smaller the current is, the better is the flicker noise performance. It is opposite to the thermal noise. Therefore, the bias current should be as small as possible as long as the thermal noise performance is satisfied. Finally, we studied the effect of the transistor size of the switch. The larger the width, the better is the noise performance. However, when the transistor width is too large, the output bandwidth effect will appear and the noise performance will become worse. Also, the oscillator can not afford a very large capacitive loading. That is to say the upper limit is bounded by LO driving ability and the output bandwidth.

VI. CONCLUSION

This paper explores the flicker noise mechanism under switching conditions through measurements. For a non-linear circuit, the flicker noise should be modelled as the noise voltage at the gate rather than as the noise current at the drain. The baseband flicker noise is independent of the input switching frequency when a sufficient output bandwidth is guaranteed. Flicker noise under switching conditions can be modelled by AM modulations and it is verified by both simulations and measurements. The noise prediction and optimization of non-linear circuits by a simple simulation becomes possible. An RF application example is given to show the noise optimization using the proposed model.

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