A Study of Phase Noise Due to Power Supply Noise in a CMOS Ring Oscillator

Se-Hoon Park, *Member, KIMICS*

Abstract—The effect of power supply noise on the phase noise of a ring oscillator is studied. The power supply noise source in series with DC power supply voltage is applied to a 3 stage CMOS ring oscillator. The phase noise due to the power supply noise is modeled by the narrow band phase modulation. The model is verified by the fact that the spectrum of output of ring oscillator has two side bands at the frequencies offset from the frequency of the ring oscillator by the frequency of the power supply noise source. Simulations at several different frequency of the power supply noise reveals that the ring oscillator acts as a low pass filter to the power supply noise. This study, as a result, shows that the phase noise generated by the power supply noise is inversely proportional to the frequency offset from the carrier frequency.

Index Terms—Ring Oscillator, Narrow Band Phase Modulation, Power Supply Noise, Phase noise

I. INTRODUCTION

Growth in the mobile wireless communication prompts the increase of the number of the communication channels. To secure the number of channels, a more stringent standard is required for the phase noise of the oscillator in the communication system since the number of channel is limited by the phase noise [1]-[3]. The phase noise is the major contributor to undesired phenomena such as interchannel interference leading to increased bit-error rates in RF communication systems. The phase noise of CMOS technology is generic due to several noise sources in CMOS circuits. Optimization of the circuit design and the process mitigates the problems to the tolerable level [4].

In digital circuits, the counter partner of the phase noise is jitter. Jitter is the variation of transition time of a periodic signal: the transition of a clock becomes out of periodic cycle when it is exposed to noise. Jitter also is important in clocked and sampled-data system: uncertainties in switching instants caused by noise lead to synchronization problems. As a result, jitter forces designers to have the larger margin for the timing calculation making the speed of system slow.

Integrated circuits made by CMOS technology suffer from multiple noise sources such as power supply noise, semiconductor device noise, and interference noise between nearby signals. The semiconductor device noise includes the 1/f noise and shot noise. Many authors have reported the effect of 1/f noise on the phase noise or the jitter [5]-[7]. Among above noise sources, the power supply noise is in general most influential one although the weight of each noise is different depending on applications.

In this study, the power supply noise modeled by a sinusoidal wave is in series with the power supply source of the ring oscillator under investigation. The sinusoidal noise source is used because the real power supply noise is the sum of sinusoidal waves of continuously distributed frequencies. And with a known noise frequency, it is easy to identify the effect of a specific noise source.

A simple model is suggested to explain the effect of the power supply noise on the phase noise. This model is simple enough to give designers a direct insight into the relation between the power supply noise and the phase noise. The ring oscillator is implemented by 0.35 μm CMOS technology. And its center frequency is at 1.97 GHz.

II. A MODEL OF THE PHASE NOISE DUE TO THE POWER SUPPLY NOISE

The power supply noise is induced by the parasitic inductor. The bonding wire connecting the bonding pad in a chip to the lead frame becomes the parasitic inductor generating the power supply noise. The power supply noise is described by

$$v_{sn} = L\frac{di}{dt} \tag{1}$$

where v_{sn} is the power supply noise, L is the total parasitic inductance at the corresponding node, and i is the power supply current. The power supply current in both analog and digital circuits is not constant but changes as input signals change. In analog circuits, the bias of transistors changes as the input signal changes resulting in the change of power supply current. In digital circuits, switching operation of transistors changes the number of current path changing the total power supply current. These varying current through the parasitic inductor generates the power supply noise.

The phase noise in a ring oscillator due to the power supply noise is modeled as variation of phase. The output of ring oscillator exposed to power supply noise, v_{out}, is

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Se-Hoon Park is with the School of Electronic & Information Engineering, Andong National University, Andong, 760-749, Korea (Tel: +82-54-820-5681, Fax: +82-54-820-5915, Email: separk@andong.ac.kr)

a square wave with a fixed frequency ω_0 and phase $\theta(t)$ as shown below.

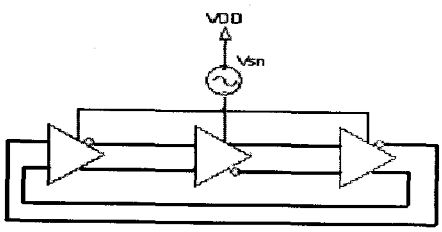
$$v_{out} = A \cdot f\left[\omega_0 t + \theta(t)\right] \tag{2}$$

where $\theta(t)$ is a function of time and determined by the power supply noise. If $\theta(t)$ is small enough, the output of ring oscillator is explained using the narrow band phase modulation. The narrow band phase modulation is similar with the amplitude modulation (AM) in generating side bands around a carrier frequency. To simplify the explanation of the narrow band phase modulation model, the function f is assumed as a sinusoidal wave. Then Eq. (2) is rewritten as follows

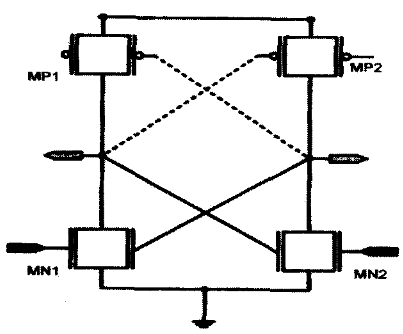
$$f(t) = \cos\omega_0 t - k_p \cos\omega_n t \sin\omega_0 t \tag{3}$$

where k_p is the coefficient of phase modulation, ω_0 is the fundamental frequency of ring oscillator, and ω_n is the frequency of power supply noise. The narrow band phase modulation converts the power supply noise into a signal at the frequency of $\omega_0 \pm \omega_n$. This feature is similar one with the amplitude modulation. This frequency conversion of noise signal was reported by Razavi [8].

To verify the narrow band phase modulation theory, a simulation is performed with the power supply noise, which is sinusoidal and in series with the power supply source. The reason why the sinusoidal noise source is used is to check the effect of a specific noise frequency on the phase noise. The noise source has the amplitude of 0.1 V and the frequency of 400 MHz. Fig. 1 shows the schematic of the ring oscillator used in this simulation. The unit inverter of Fig. 1(b) has smaller delay time than simple inverter because of the latched circuit configuration.



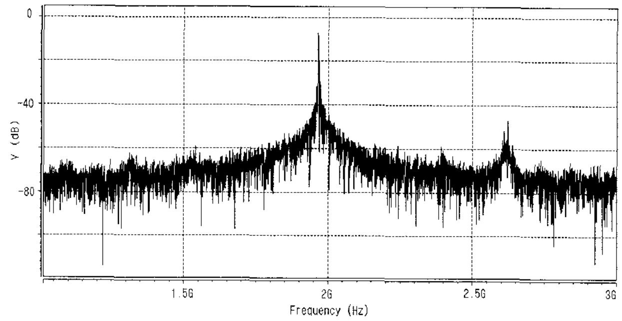
(a)



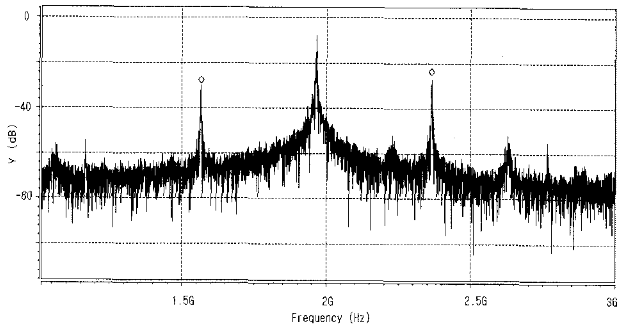
(b)

Fig. 1 (a) A schematic of ring oscillator with power supply noise, (b) Circuit of individual inverter of the ring oscillator.

Fig. 2 shows the Fourier transforms of ring oscillator output voltage: (a) with no the power supply noise (b) with the power supply noise. In the case of no power supply noise, there is only a signal peak at the frequency of 1.97 GHz. But with power supply noise, there are signal peaks offset from the frequency of ring oscillator by the amount of the frequency of the power supply noise. This fact verifies the model of the narrow band phase modulation accounting for the phase noise due to the power supply noise.



(a) Without power supply noise



(b) With power supply noise

Fig. 2 Comparison of output spectrums of ring oscillator: Peaks with small circles are due to the power supply noise.

The simulation result of Fig. 2 is just for the power supply noise of 400 MHz. Real power supply noise is composed of continuously distributed sinusoidal signals. As a result, it is predictable that the real power supply noise would make the output spectrum of ring oscillator spread over some range of frequencies, which is called the phase noise.

By simulating at several different frequency of power supply noise, it is possible to draw the shape of the phase noise due to the power supply noise. Fig. 3 shows the ratio of the sideband noise voltage to the fundamental signal voltage with changing frequencies of the power supply noise from 200 MHz to 600 MHz. The sideband noise voltage drops as frequency increases with slope of $f^{-0.9}$ that is very close to 1/f. In other words, the side band noise voltage has an envelop of output voltage expressed by 1/s in the frequency domain. This fact leads to the fact that the ring oscillator acts like a low pass filter having the power supply noise as an input and the output of ring oscillator as the output. The transfer function of the low pass filter $T(s)$ is simply given as following

$$T(s) = \frac{1}{1 + s/\omega_k} \approx \frac{\omega_k}{s} \qquad (4)$$

where ω_k is the characteristic angular frequency of the ring oscillator and very small. As a result, the ring oscillator acts as a single pole low pass filter for the power supply noise. To make the characteristic angular frequency small for low phase noise, it is recommended to have small capacitances in ring oscillator circuits as possible as it can be.

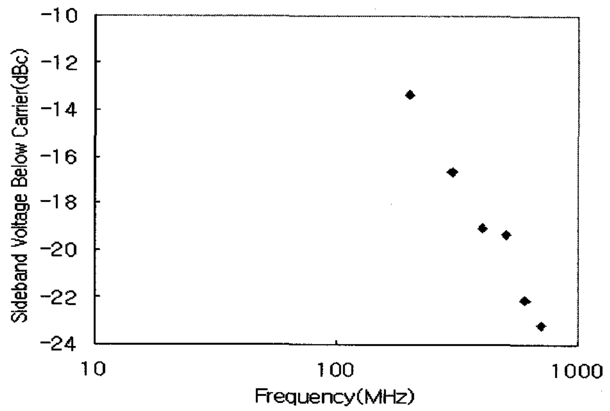


Fig. 3 Ratio of the sideband noise voltage to the fundamental signal voltage as a function of the frequency of the power supply noise source.

IV. CONCLUSIONS

The effect of the power supply noise on the phase noise of a ring oscillator is investigated. It is verified by simulation that the power supply noise is converted into the phase noise by the narrow band phase modulation. The frequency of the power supply noise is converted into around the frequency of ring oscillator ($\omega_0 \pm \omega_n$) by the modulation. Simulation at several different frequencies of the power supply noise reveals that the phase noise due to the power supply noise is inversely proportional to the frequency. The simulation also shows that the ring oscillator acts as a low pass filter with a very low value of pole.

The suggested model gives a direct insight into the mechanism of generation of the phase noise due to the power supply noise.

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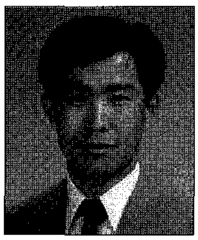

Se-Hoon Park
Received the B.S. and M.S. degrees in Electronic Engineering from Kyung Pook National University, Korea in 1980 and 1982 respectively and Ph.D. in Electrical Engineering from Arizona State University, USA in 1993. From 1983 to 1986, he was with Semiconductor Division of Hyundai Electronics. From 1993 to 1995, he was a senior engineer at ETRI, Korea. He is an associate professor at Electronic & Information Engineering, Andong National University, Korea. His research interest is in the design of analog and digital communication systems.