An N-path Filter Enhanced Low Phase Noise Ring VCO

Chunyang Zhai, Jeffrey Fredenburg, John Bell, and Michael P. Flynn
University of Michigan, Ann Arbor
{zhaicy, fredenbu, johnlb, mpflynn}@umich.edu

Abstract

A novel self-filtering scheme breaks the typical tradeoff between noise and power, enabling a ring oscillator to approach the phase noise performance of an LC oscillator. The prototype N-path filter enhanced voltage-controlled ring oscillator (NPFRVCO) achieves a measured phase noise of -110dBc/Hz at a 1MHz offset frequency for an oscillation frequency of 1.0GHz. The self-clocked N-path filter reduces the phase noise by 10dB and 28dB for 1.0GHz and 300MHz oscillation frequencies, respectively. Implemented in 65nm CMOS, the NPFRVCO occupies a die area of 0.015 mm^2 and consumes 4.7mW from 1.2V power supply when operating at 1.0GHz. The NPFRVCO has a measured frequency tuning range from 300MHz to 1.6GHz and achieves a FoM of 163dB at 1MHz offset.

Introduction

CMOS ring oscillators consume significantly less silicon area than integrated resonator-based LC oscillators and do not require high-Q inductors. They also achieve much wider tuning range than LC oscillators and can easily generate multiple phases [1]. On the other hand, LC oscillators offer better phase noise and provide higher supply noise rejection.

Recent researches on ring oscillators offer various techniques to improve the phase noise performance. In [2], a source-follower-based delay multipath ring oscillator is proposed to improve the supply rejection of the delay cell. In [3], a reference phase alignment technique reduces in-band phase noise. Other approaches rely on LC band-pass filtering structures tuned to the oscillation frequency, such as [4], where LC band-pass filters serve as the load to each of the ring oscillator stages. These filters, however, tend to be large and suffer from a limited tuning range.

In this work, we present a novel self-filtering technique for oscillators based on band-pass N-path filters, and demonstrate a ring oscillator with wide tuning range and a phase noise performance comparable to LC oscillators. Although this proposed self-filtering scheme incurs a small increase in power consumption, no additional reference or control circuitry is needed. The prototype NPFRVCO achieves a phase noise of -110dBc/Hz at 1MHz offset for a 1.0GHz operating frequency. At 300MHz, 1.0GHz the measured phase noise is 28dB, 10dB, respectively, better than a comparable coupled ring VCO without N-path filtering.

N-Path Filter Enhanced Ring VCO

The conceptual implementation of the NPFRVCO is provided in Fig. 1(a). As shown, two identical ring oscillators (A and B) are cross-coupled through two continuous-time band-pass N-path filters (FA and FB). The output from each ring oscillator is first band-pass filtered by an N-path filter structure and then injected into the other ring.

An N-path filter is comprised of N capacitors connected in turn to the signal source through a resistor and one of N switches, controlled by N non-overlapping clock signals. An N-path filter transfers a low-pass RC filter characteristic to a high frequency band-pass characteristic [5] to achieve a high quality factor Q. Because the resulting band-pass filter has twice the 3dB bandwidth of the low-pass RC filter, N-path filters achieve a high Q using only resistors, capacitors and switches. The center frequency of the band-pass filter is at the N-path clocking frequency. With the N-path band-pass filters, the spectral content of injected coupling signals becomes more narrow-band, as shown in Fig. 1(b), which reduces the overall phase noise with only a small power penalty (23%).

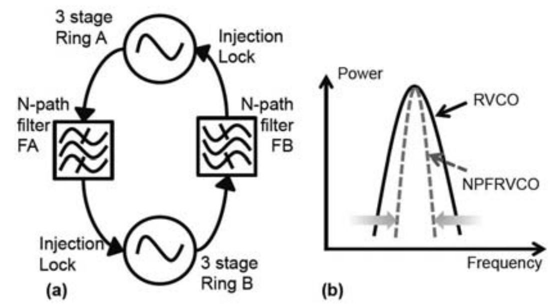

Fig. 1 N-path filter enhanced ring VCO concept

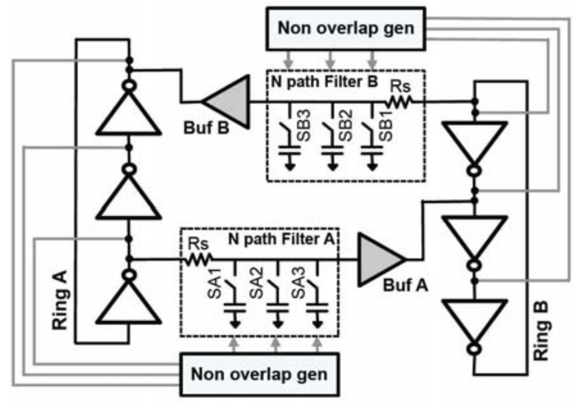

Fig. 2 NPFRVCO block diagram (The actual implementation is fully differential).

This new self-filtering approach has advantages over other filter approaches that rely on LC structures. LC structures tend to be large and limit the tuning range. Instead, our filtering approach does not need inductors, as the N-path filters are constructed with only switches, resistors and capacitors. Furthermore, the N-path filter provides a significant advantage for tuning range capabilities since the center frequency of the N-path filters inherently tracks the VCO oscillation frequency as a result of a self-clocking technique.

Fig. 2 shows a detailed block diagram of the cross-coupled NPFRVCO (The overall coupled oscillator is differential, but a single ended version is shown in Fig. 2 for clarity). The two oscillators, Rings A and B, are coupled through two N-path filters, with each N-path filter constructed using three-paths and followed by a buffer to generate the coupling injection signal. Each of the three-path filters is controlled by three non-overlapping switch signals (SA1, SA2 and SA3), which are conveniently derived from the outputs of respective three-stage rings with the help of a non-overlapping clock generator. In this way, taps from Ring A control the N-path filter FA, which inject into Ring B after being filtered, and vice-versa.

It is important to note that the clocking for these N-path filters is seamlessly generated by the oscillator structure itself. This is unlike other N-path filter applications [5], where clocking is ultimately derived from a crystal reference. This self-clocking is feasible because the strongest coupling occurs when both rings converge to the same oscillation frequency. The coupled oscillators are each differential and use a tunable differential delay cell with NMOS input and tunable PMOS loads [1].

Measurement Results

The prototype NPFRVCO is fabricated in 65nm CMOS. For comparison, we fabricated both the NPFRVCO and an identical, coupled two-ring VCO but without N-path filtering. The NPFRVCO consumes 4.7mW from 1.2V power supply when operating at 1.0GHz. At the same frequency the oscillator without N-path filtering consumes 3.8mW. At 1.0GHz, the measured phase noise (measured with an Agilent E5052B signal source analyzer) at a 1MHz offset is -110dBc/Hz. The measured phase noise for the comparable coupled oscillator circuit, without N-path filtering, is -100dBc/Hz, as shown in Fig. 3. Both noise measurements are the average of 10 successive measurements and the variance is approximately 1dB. This improvement in phase noise of more than 10 dB is achieved with only a 23% increase in power consumption. Fig. 4 shows the measured variation of the phase noise at a 1MHz offset versus oscillation frequency. The phase noise difference between the NPFRVCO and the comparable cross-coupled RVCO shows more improvement at lower VCO frequencies (i.e. 28dB at 1MHz offset from the carrier at 300MHz). Furthermore, the NPFRVCO provides a consistent phase noise performance over the frequency tuning range. The frequency tuning range is 1.6GHz, around 75%. The active die area of NPFRVCO is 0.015 mm^2 and the die micrograph is show in Fig 7

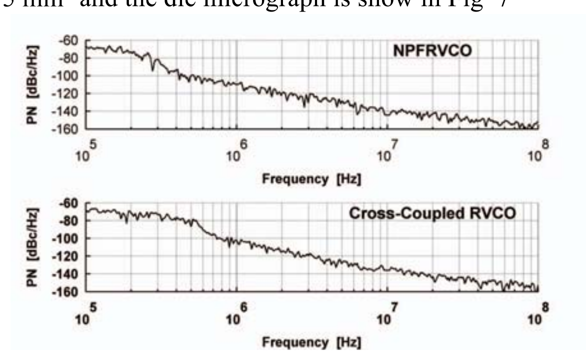

Fig. 3 Phase noise at 1MHz offset from the carrier at 1.0GHz

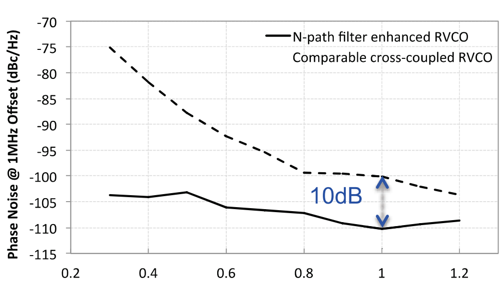

Fig. 4 Phase noise vs. frequency at 1MHz offset from carrier

Based on the standard FoM for oscillators [1], summarized comparisons of FoM, active area and tuning range between this work, the state-of-art LC oscillator designs and CMOS ring oscillator designs are shown in Fig.5 and Fig.6. As shown, although LC oscillators achieve better FoM, the silicon cost is larger than that of the CMOS ring oscillators by an order of magnitude and tuning range falls far behind that of CMOS ring oscillators. The FoM of the NPFRVCO approaches that of the LC oscillators while it takes advantage of the smaller area and wider frequency tuning range that it inherits from the CMOS ring oscillator structure.

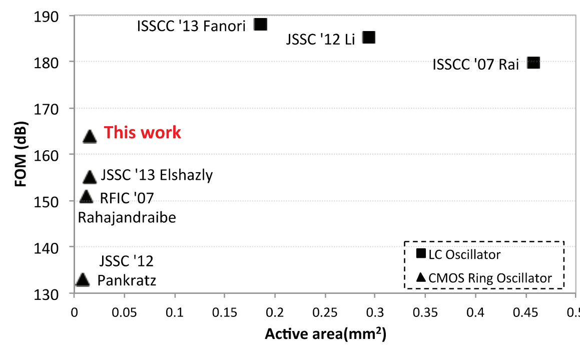

Fig. 5 FoM vs. active area

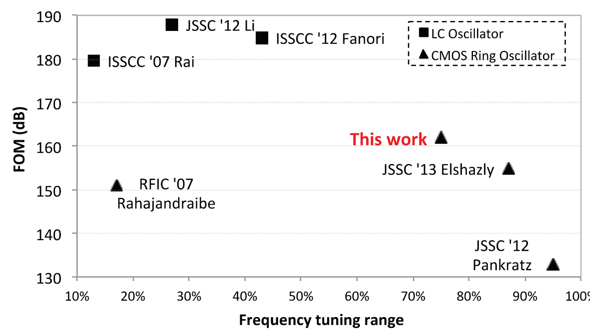

Fig. 6. FoM vs. frequency tuning range

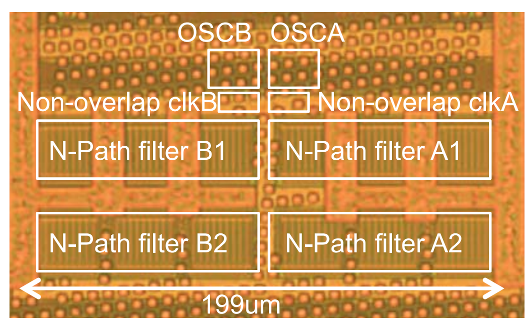

Fig. 7 Die micrograph

Acknowledgements

The authors thank Berkeley Design Automation (BDA) for simulation software.

References

[1] A. Abidi et al., JSSC, 2006, pp.1803-1816.
[2] E. Pankratz et al., JSSC, 2012, pp.2033-2048.
[3] J. Borremans et al., JSSC, 2009, pp.1942-1949.
[4] A. Ismail et al., ISSCC, 2003, pp.98-99.
[5] A. Ghaffari et al., JSSC, 2011, pp.998-1010