

## 25.4 A 1/f Noise Upconversion Reduction Technique Applied to Class-D and Class-F Oscillators

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The 1/f (flicker) noise upconversion degrades the close-in spectrum of CMOS RF oscillators. The resulting 1/f<sup>3</sup> phase noise (PN) can be an issue in PLLs with a loop bandwidth of <1MHz, which practically implies all cellular phones. A previously published noise-filtering technique [1] and adding resistors in series with g<sub>m</sub>-device drains [2] have shown significant reduction of the 1/f<sup>3</sup> oscillator PN corner. However, the former needs an additional tunable inductor and the latter degrades PN in the 20dB/dec region.

The flicker noise can upconvert via two major phenomena. First, tail current flicker noise can modulate the oscillating waveform amplitude, which can convert to PN through a nonlinear C-V characteristic of varactors and active devices. The second mechanism is the Groszkowski effect [3]: The presence of harmonic components of the active g<sub>m</sub> device current can cause a frequency drift of the tank resonance (see Fig. 25.4.1-top). The fundamental drain current I<sub>H1</sub> flows into R<sub>p</sub> (equivalent parallel resistance of the tank), while its 2<sup>nd</sup>- and 3<sup>rd</sup>-harmonic components, I<sub>H2</sub> and I<sub>H3</sub>, mainly take the capacitance path due to its lower impedance. Consequently, the reactive energy stored in the inductance and capacitance is perturbed, shifting the oscillation frequency Δω lower to satisfy the resonance condition. This shift is static but any variation in the I<sub>H2</sub> (or I<sub>H3</sub>)-to-I<sub>H1</sub> ratio due to the 1/f noise can modulate Δω and show itself as the 1/f<sup>3</sup> PN, see Fig. 25.4.1(top-left). This phenomenon is clearly visible and now *dominant* in oscillators with the customary tail current source transistor removed, which is the trend in nanoscale CMOS.

Suppose the tank input impedance Z<sub>in</sub> demonstrates other peaks at the strong harmonics of the fundamental frequency ω<sub>0</sub>. These harmonics would mainly flow into their relative equivalent resistance of Z<sub>in</sub> instead of its capacitive part, as is shown in Fig. 25.4.1-bottom. Consequently, Groszkowski's effect on the 1/f noise up-conversion will reduce significantly. Specifically core transistor flicker noise modulates the 2<sup>nd</sup> harmonic of the oscillator's virtual ground. This modulation generates 2<sup>nd</sup>-harmonic current in the parasitic C<sub>gs</sub> capacitors and gets injected to the tank. Consequently, the I<sub>H2</sub> component is usually the main contributor to the frequency shift. In this work we introduce a tank topology that effectively traps I<sub>H2</sub> in its resistive part without the cost of an extra area. The tank derives this characteristic from the different behavior of inductors and transformers in differential (DM) and common mode (CM) excitations.

Figure 25.4.2 shows a 2-turn inductor in DM and CM excitations. In DM, the currents in each turn are in the same direction resulting in an additive flux, while in CM, the opposite currents cancel each other's magnetic flux. Due to this cancellation, the effective CM inductance is very low. The "F<sub>2</sub> inductor" is designed with appropriate spacing between the windings and demonstrates a 4x smaller effective inductance for CM inputs than for DM inputs. The CM input signals cannot see the differential capacitances, hence to be able to set a CM resonance, the capacitors across the tank have to be single-ended. The input impedance of the F<sub>2</sub> tank, Z<sub>in</sub>, demonstrates two resonant frequencies, ω<sub>DM</sub>=ω<sub>0</sub>, and ω<sub>CM</sub>=2ω<sub>0</sub>. The precise inductor geometry controlled by lithography maintains L<sub>DM</sub>/L<sub>CM</sub>≈4 and hence ω<sub>CM</sub>/ω<sub>DM</sub>≈2 over the full tuning range, TR. The lower and broader CM impedance, compared to that of DM, guarantees the 2<sup>nd</sup>-harmonic current flowing mainly to the additional resistive part, even if CM resonant frequency is mis-tuned by 10%.

Figure 25.4.3 shows a 1:2 turns ratio transformer excited by DM and CM input signals at its primary. In DM excitation, the induced currents at the secondary circulate in the same direction leading to a strong coupling factor, k<sub>m</sub>. On the other hand, in CM excitation, the induced currents cancel each other, resulting in a weak k<sub>m</sub>. The "F<sub>2,3</sub> tank" employs the F<sub>2,3</sub> transformer, single-ended primary and differential secondary capacitors. This tank has two DM and one CM resonant frequencies. For resistive traps at 2<sup>nd</sup> and 3<sup>rd</sup> harmonics, ω<sub>CM</sub>=2ω<sub>0,DM</sub> and ω<sub>1,DM</sub>=3ω<sub>0,DM</sub>, resulting in L<sub>s</sub>C<sub>s</sub>=3L<sub>p</sub>C<sub>p</sub> and k<sub>m</sub>=0.72 [4]. In reality, L<sub>pc</sub>>L<sub>pd</sub> due to the metal track inductance L<sub>t</sub> connecting the center tap to the supply, thus lower k<sub>m</sub> is needed to satisfy both F<sub>2</sub> and F<sub>3</sub> operations. Unlike the F<sub>2</sub> tank, in the F<sub>2,3</sub> tank, the ω<sub>CM</sub>/ω<sub>0,DM</sub> and ω<sub>1,DM</sub>/ω<sub>0,DM</sub> ratio is no longer only dependent on the inductive parts. Careful design of the tunable single-ended primary and differential secondary capacitor banks maintains ω<sub>CM</sub>/ω<sub>0,DM</sub>≈2 and ω<sub>1,DM</sub>/ω<sub>0,DM</sub>≈3 over the full TR.

To demonstrate how this technique can reduce the flicker noise upconversion, we employ the F<sub>2</sub>-tank to a Class-D [5], and F<sub>2,3</sub>-tank to a Class-F [4] oscillator. These classes of oscillator are chosen for their strong amount of I<sub>H2</sub>.

The original Class-D oscillator shows promising performance in the 1/f<sup>2</sup> region but it suffers from the strong 1/f noise upconversion and frequency supply pushing. All known mitigation techniques (e.g., [6]) seem either ineffective or unsuitable. As shown in Fig. 25.4.4-top, the Class-D/F<sub>2</sub> oscillator adopts the F<sub>2</sub> tank. The g<sub>m</sub>-devices M<sub>1</sub> and M<sub>2</sub> inject a large I<sub>H2</sub> current into the tank due to the ground-clipping of signals. Figure 25.4.4 also compares Class-D and D/F<sub>2</sub> waveforms. Clearly the rise/fall times are more symmetric in the Class-D/F<sub>2</sub> oscillator, which translates to lower DC value of the g<sub>m</sub>-transistor ISF function and thus lowers the 1/f noise up-conversion. The Class-D oscillator shows 0.8 to 2.5MHz 1/f<sup>3</sup> corner frequency. A version of Class-D with a tail-filter technique [6] was also designed in [5]. A resonator at 2ω<sub>0</sub> is interposed between the common source of the transistors and ground. This method is only partially effective, lowering the 1/f<sup>3</sup> PN corner to 0.6 to 1MHz, since it only linearizes the g<sub>m</sub> device and partially reduces the I<sub>H2</sub> amount. Our method traps I<sub>H2</sub> in the tank and simulations predict the 1/f<sup>3</sup> PN corner of <50 kHz.

The Class-F<sub>3</sub> oscillator has a pseudo square-wave oscillation waveform by designing ω<sub>1,DM</sub>=3ω<sub>0,DM</sub>, and avoiding filtering of I<sub>H3</sub> in the tank. The special ISF function of square waveform oscillation leads to a better PN performance. Simulations show that in this oscillator I<sub>H2</sub> can be as high as I<sub>H3</sub>. The Class-F<sub>2,3</sub> oscillator replaces the Class-F<sub>3</sub> tank with the F<sub>2,3</sub> one, as shown in Fig. 25.4.4-bottom. Simulations show that the pseudo square wave of Class-F is preserved and the 1/f<sup>3</sup> PN corner can be reduced from 300 to 700 kHz to <30 kHz.

The Class-D/F<sub>2</sub> oscillator was prototyped in a 40nm 1P8M CMOS process *without* ultra-thick metal layers. The chip micrograph is shown in Fig. 25.4.7-left. The tank employs a 1.5nH inductor with simulated Q-factor of 12 at 3GHz. M<sub>1,2</sub> are (200/0.04)μm low-V<sub>t</sub> devices which guarantee start-up and Class-D operation over PVT. The oscillator is tunable between 3.3 and 4.5GHz (31% TR) with a 6b MOM capacitor bank. Figure 25.4.5-top shows the PN plots at f<sub>max</sub> and f<sub>min</sub> oscillation frequencies, with V<sub>DD</sub>=0.5V. The 1/f<sup>3</sup> PN corner is ~100kHz at f<sub>max</sub> and reduces to 60kHz when all switches are on at f<sub>min</sub>.

The Class-F<sub>2,3</sub> oscillator was prototyped in a 40nm 1P7M CMOS process *with* an ultra-thick metal layer (see Fig. 25.4.7-right). The tank primary and secondary are 0.58nH and 1.5nH, respectively, and k<sub>m</sub>=0.67. The simulated Q-factors of the primary and secondary windings are 13 and 19 at 5GHz. M<sub>1,2</sub> are (64/0.27)μm thick-oxide devices to tolerate large gate voltage swings. The oscillator is tunable between 5.4 and 7 GHz (25% TR) with two 6b MOM capacitor banks. Figure 25.4.5-bottom shows the PN plots at f<sub>max</sub> and f<sub>min</sub> oscillation frequencies, with V<sub>DD</sub> of 1V. The 1/f<sup>3</sup> PN corner is ~130kHz at f<sub>max</sub> and reduces to 60kHz when all switches are on at f<sub>min</sub>.

In both oscillators the PN in the 1/f<sup>2</sup> region fits well with the simulations. However, the 1/f<sup>3</sup> PN corner is at least ~2x higher than expected mainly due to a 2ω<sub>0</sub> disturbance on the supply rail created by the oscillator output buffer. Fig. 25.4.6 summarizes the oscillator performances and compares them with their counterpart reference designs. Even with the performance degradation due to the unavoidable supply sharing, this technique demonstrates >10-to-15x improvement in the 1/f<sup>3</sup> PN corner in Class-D and 5x improvement in Class-F with no extra area penalty. It also significantly improves supply pushing.

### Acknowledgments:

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### References:

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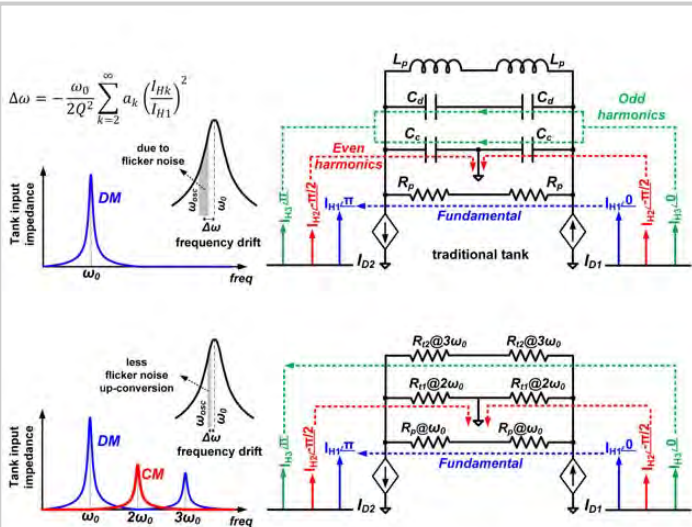


Figure 25.4.1: Current harmonic paths and frequency drift.

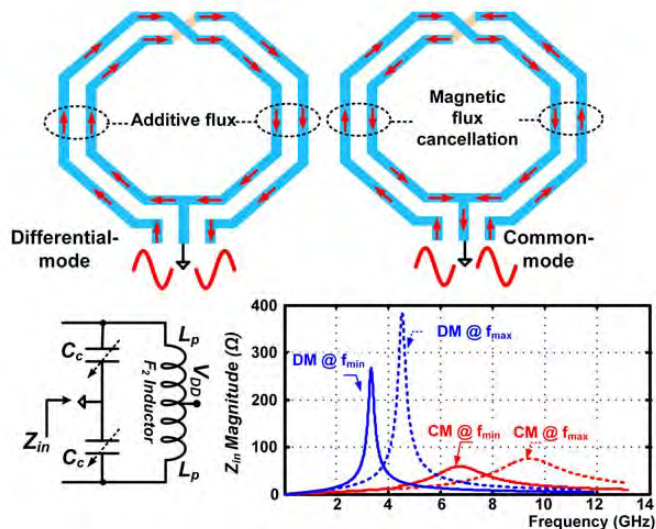


Figure 25.4.2: F<sub>2</sub> inductor, F<sub>2</sub> tank and tank Z<sub>in</sub>.

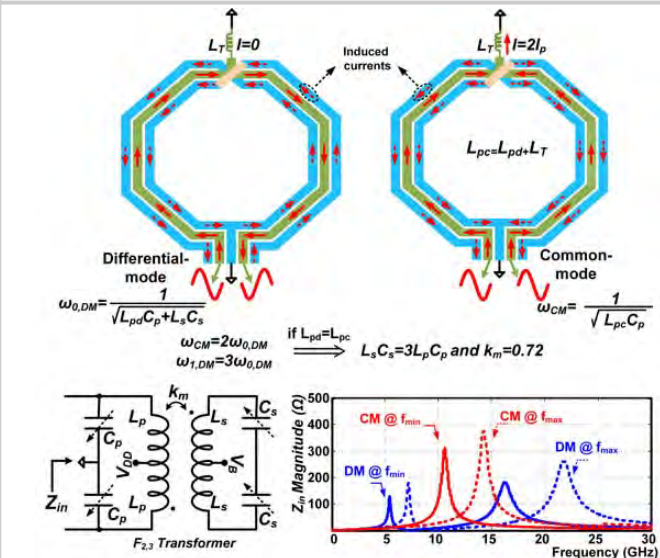


Figure 25.4.3: F<sub>2,3</sub> transformer, F<sub>2,3</sub> tank and tank Z<sub>in</sub>.

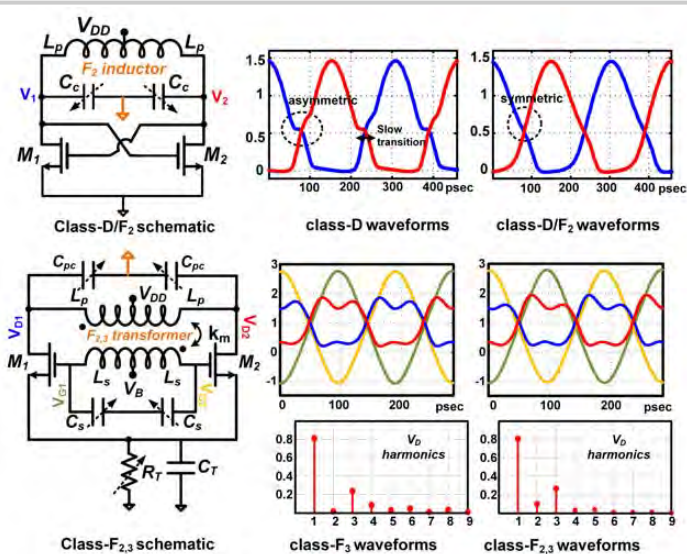


Figure 25.4.4: Oscillator schematics and waveforms.

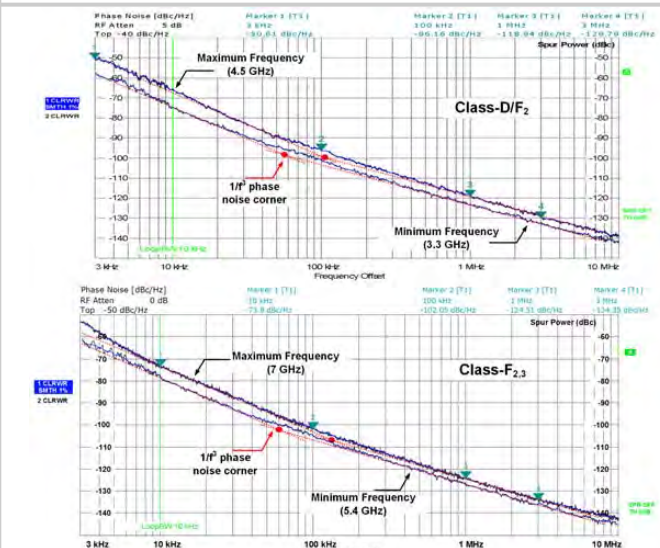


Figure 25.4.5: Measured oscillator PNs.

	Class-D/F <sub>2</sub>		Class-D [5]		Noise Filtering Class-D [5]		Class-F <sub>2,3</sub>		Class-F <sub>2,3</sub> [4]	
Technology	40 nm		65 nm		65 nm		40 nm		65 nm	
Thick metal	No		Yes		Yes		Yes		Yes	
V <sub>DD</sub> (V)	0.5		0.4		0.4		1		1.25	
Tuning range (%)	31		45		45		25%		25%	
OSC core area	0.1 mm <sup>2</sup>		0.12 mm <sup>2</sup>		0.15 mm <sup>2</sup>		0.13 mm <sup>2</sup>		0.12mm <sup>2</sup>	
Freq. (GHz)	f <sub>min</sub>	f <sub>max</sub>	f <sub>min</sub>	f <sub>max</sub>	f <sub>min</sub>	f <sub>max</sub>	f <sub>min</sub>	f <sub>max</sub>	f <sub>max</sub>	
	3.3	4.5	3	4.8	3	4.8	5.4	7	7.4	
P <sub>DC</sub> (mW)	4.1	2.5	6.8	4	6.8	3.6	12	10	15	
	100kHz	-101.2	-96.2	-101	-91	-102	-92.5	105.3	102.05	-98.5
PN (dBc /Hz)	1MHz	-123.4	-119	-127	-119	-128	-121	126.7	124.5	-125
	10MHz	-143.4	-139	-149.5	-143.5	-150	-144.5	146.7	144.5	-147
	100kHz	185.4	185.3	182.2	178.6	183.2	180.56	189.1	188.9	184.1
FoM <sup>1</sup> (dB)	1MHz	187.6	188	188.2	186.6	189.2	189.06	190.5	191.4	190.6
	10MHz	187.6	188	190.7	191.1	191.2	192.56	190.5	191.4	192.6
	1/1 <sup>st</sup> corner (kHz)	60	100	800	2100	650	1500	60	130	700
Freq. pushing (MHz/V)	40	60	140	480	90	390	12	23	50	
	@0.5V	@0.5V	@0.5V	@0.5V	@0.5V	@0.5V	@1V	@1V	@1.25V	

<sup>1</sup>FoM = |PN| + 20 log<sub>10</sub>(ω/Δω) - 10 log<sub>10</sub>(P<sub>DC</sub>/1mW)

Figure 25.4.6: Comparison with relevant oscillators.

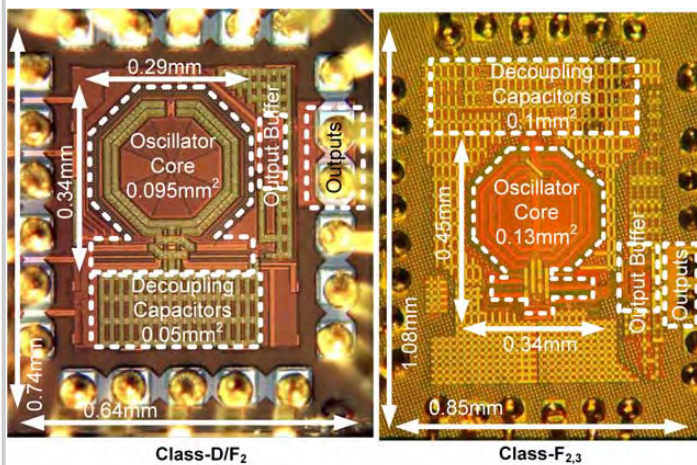


Figure 25.4.7: Die micrographs.