Time-Dependent Single-Event Effects in CMOS LC-oscillators

Jeffrey Prinzie, Valentijn De Smedt

Abstract—This paper presents a general theory of time-dependent Single-Event Effects in CMOS LC-oscillators. The analysis employs the oscillator's Impulse Sensitive Function (ISF) to calculate the effect of a transient current due to an ionizing particle. A discussion is made on the dependence of the maximum junction collection current and the modulation of this current with the VCO signal waveform, supported by TCAD simulations. An experimental study using a Two Photon Absorption (TPA) laser setup is performed to obtain accurate measurements of the time-dependent charge-to-phase transfer function of the oscillator.

Index Terms—Single-Event Upsets (SEUs), Radiation Hardening by Design, Oscillators, Impulse Sensitive Function, Two Photon Absorption laser.

I. INTRODUCTION

TIME precision is a key performance indicator in a wide range of modern integrated circuits and systems. This precision refers to the stability, noise and accuracy of a reference clock signal to the system. In a vast majority of systems, a crystal oscillator reference clock in combination with a high-speed Phase Locked Loop (PLL) is used to synthesize a high-frequency on-chip signal that can act as a digital clock signal, stable time reference or local oscillator (LO) frequency for up- and down-conversion of communication signals. Integrated Voltage Controlled Oscillators (VCOs) are the main and critical blocks that determine the performance and noise of the synthesized clock signals, which are controlled in a closed loop PLL and are locked to a stable reference clock.

High precision timing circuits are widely employed in applications with moderate and high levels of ionizing radiation. Such applications are high-speed serial communication links, high-precision Time-of-Flight measurements and wireless communication systems. Radiation effects on CMOS circuits have been studied elaborately before. Total Ionizing Dose (TID) effects are destructive ionization effects which degrade CMOS transistors over time. TID studies have been reported up to Grad dose levels [1], which are expected at future accelerator and detector environments in high-energy physics experiments [2]. In contrast to long term TID effects, Single-Event Effects (SEEs) instantaneously disturb the operation of an integrated circuit by depositing an amount of charge in the silicon substrate, which is captured in the transistors' junctions [3]–[5].

Radiation hardening of PLLs, and VCOs in particular, has been an interesting topic due to the importance of this block.

Many attempts have been made to study and understand radiation effects on VCOs and PLLs. Two commonly used types of integrated VCOs are ring oscillators and LC-tank oscillators. Ring oscillators consist of a ring of CMOS gates, which are either single-ended or differential. The oscillation frequency is determined by the total loop delay. In contrast, LC-tank oscillators employ a resonant tank in combination with an amplifier that compensates for losses in the tank. LC-tank oscillators show superior phase noise figures at the cost of larger silicon area due to the size of the inductor.

In the past, many work was done on protecting ring oscillators, LC-tank oscillators and PLLs against Single Event Effects, by design. In [6] and [7], a modeling technique has been discussed involving design techniques to reduce transients in CMOS ring oscillators, mainly focusing on the biasing circuits of these oscillators. Despite this, missing cycles have been reported due to particle strikes. Fortunately, Triple Modular Redundancy (TMR) can be employed in ring oscillators [8]. Not only VCOs require attention, however also radiation effects on the loop filter of a PLL need to be addressed, which cause frequency transients or loss of lock [9]. High bandwidth loop dynamics help to suppress the integrated phase error and reduce recovery time [10]. In [11], a linear model was used to study transient effects in closed loop PLLs, stressing the effect of the loop dynamics on the recovery time. Several other methods have been proposed to diminish the SEE sensitivity of PLLs [12] [13]. Radiation hardening techniques for LC-tank oscillators were addressed in [14]–[17]. In [14] and [15], an RC filtering network was used to suppress transients from tail current sources, a commonly used technique in practical implementations. In [17], a novel circuit implementation was proposed addressing radiation effects in CMOS varactors which tune the tank. In the vast majority of these references, a specific problem of the circuit is assessed, but lacking a systematic hardening approach and fundamental analysis of charge-to-phase conversion in an oscillator.

This paper addresses the fundamental background of single-event radiation effects on CMOS LC oscillators. These effects are time dependent since the magnitude of the error depends on the moment that the particle hits the circuit. An initial proposal was made in [18], which confirmed the time dependency of errors in oscillators but did not address charge collection mechanism and modulation due to the large signal, high-speed waveform of the oscillator. Furthermore, no experimental verification has been reported that study these effects in practice. In [19], laser experiments were performed but measurements were observed in the frequency domain such that any time dependent information was lost. In [20], time-

The authors are with the Dept. Electrical Engineering (ESAT-ADVISE), KU Leuven, Belgium. Email: Jeffrey.Prinzie@kuleuven.be.

This work was supported by the FWO.

dependent effects on high-speed mixed-signal circuits were studied by correlating the number of errors to the event-time of the upset. In this paper the time-dependent phase error and especially its magnitude is further used to analyze the severity of the occurred transients. A full understanding of these mechanisms can eventually lead to new hardening approaches.

This paper is organized as follows: In section II, a theoretical study is presented on the time-dependent phase errors in oscillators. In section III, a large signal analysis is made with respect to the junction collection currents for small and large charge densities. Finally, in section IV, experimental results are shown proving the time dependency of phase errors with laser experiments.

II. TIME-DEPENDENT PHASE ERRORS IN OSCILLATORS

Oscillators are large signal, periodic circuits which generate output signals without any input. In resonant LC-oscillators, the oscillator's waveform is a sinusoidal with only little harmonics at higher orders. The impedance of a parallel RLC tank (fig. 1) can be written as:

$$Z(j\omega) = j\omega L \frac{\omega_0^2}{(\omega_0^2 - \omega^2) + j\omega \frac{\omega_0}{Q}} \quad (1)$$

where $\omega_0^2 = 1/LC$ and Q is the quality factor of the tank, equal to the total quality factor of both the inductor and capacitor of the tank. The size of these components strongly depends on the (tunable) frequency of the tank. To obtain a stable oscillation, a negative resistance needs to be added in parallel to compensate for the losses in the tank. This results in an oscillation frequency $f = 1/(2\pi\sqrt{LC})$.

Fig. 1: Ideal LC tank with a negative resistance to compensate for the losses in the tank. An impulse charge Q_{inj} is injected to the tank at different moments in time.

When a current impulse with charge Q_{inj} is injected to the tank, as shown in Fig. 1, all charge is entirely deposited to the capacitor, which leads to a voltage step of Q_{inj}/C . The extend to which this charge contributes to a phase error highly depends on the moment when the charge is injected. When the charge is injected near the peak of the signal, more energy is added to the tank but the phase error is zero. When the charge is injected near the zero crossing of the signal, it contributes most to a phase error, as shown in Fig. 2. Note that the excess amplitude will disappear since the circuit cannot sustain this amplitude. In most cases, excess amplitude or

amplitude transients are neglected since the oscillators are typically succeeded by a saturating buffer which removes all deviations.

Fig. 2: Charge injection at different times of the LC tank: a) at the signal zero crossing and b) at the signal peak.

The time dependent sensitivity of phase errors has been studied in detail to analyze phase noise in oscillators [21]. By treating an oscillator as a Linear Time-Variant (LTV) system, the conversion of different noise sources towards phase noise around the fundamental frequency can be explained. In practice, every oscillator is characterized by a periodic Impulse Sensitive Function (ISF), which models the time dependent conversion between the injected charge and the resulting phase error [22]. The ISF is a periodic function which is independent of the amplitude and oscillation frequency. It only depends on the (normalized) shape of the waveform and the periodic large signal behavior of the circuit. This leads to a Linear Time-Variant impulse response of the phase:

$$h_\phi(t, \tau) = \frac{1}{q_{max}} \Gamma(\omega\tau) u(t - \tau) \quad (2)$$

where $\Gamma(\omega t)$ is the periodic ISF of the oscillator, τ the moment when the charge is injected, q_{max} the maximum charge on the capacitor and $u(\cdot)$ the unit step function modeling the induced phase step caused by the charge injection. As such, the phase displacement depends on the time when the charge is injected since the state of the oscillator periodically varies over time.

When an arbitrary current $i(t)$ is injected to the tank, the resulting phase shift equals [22]:

$$\phi(t) = \int_{-\infty}^{+\infty} h_\phi(t, \tau) i(\tau) d\tau = \int_{-\infty}^t \frac{1}{q_{max}} \Gamma(\omega\tau) i(\tau) d\tau \quad (3)$$

This can be explained intuitively since a current waveform is a sum of charge impulses which lead to an accumulated

phase error, taking into account that the impulse sensitivity $\Gamma(\omega t)$ is time dependent. Eq. (3) is used later to calculate the phase transient from current, captured by a transistor from an ionizing particle. For a white noise source, it can be shown that this formula results in the typical $1/f^2$ noise shape around the carrier [22].

In (2), q_{max} is the charge swing across the tank and can also be expressed as $C \cdot V_a$ where V_a is the amplitude of the oscillator. The calculation of the ISF of an oscillator is beyond the scope of this paper, however, for a second order system like an LC oscillator the following formula can be used [22]:

$$\Gamma = \frac{f'}{f'^2 + f''^2} \quad (4)$$

in which f is the output waveform shape with periodicity of 1, scaled to a unit-less amplitude of 1 and f' and f'' are the first and second derivatives respectively. For sinusoidal waveforms, $f'^2 + f''^2 = 1$, resulting in an ISF equal to f' :

$$\Gamma(\omega t) = \cos(\omega t) \quad (5)$$

In practical analysis of specific circuits, as shown later, the ISF can alternatively be found from simulation by injecting narrow charge pulses at various moments in the oscillation cycle, or by using periodic circuit analysis techniques (Periodic Steady State). As shown in [22] the linearity of the response to a charge injection can easily be proved in simulation for all practical cases. However, as will be demonstrated in the next paragraph, when the collection rate of the injected charges is limited and time dependent, a distinction based on charge amplitude is unavoidable, requiring an extension to the LTV model.

III. WAVEFORM DEPENDENT CHARGE COLLECTION

Ionizing radiation induces the generation of free electron-hole pairs in its trajectory which can be captured and injected to the circuit through the drain and source junctions of the devices. While this mechanism is complex, it can be generalized as a combination of drift and diffusion currents near the junctions.

The physics behind the charge collection has elaborately been studied before and has been applied on both analog and digital circuits. One of the key aspects to analyze the time-dependent effects in oscillators is the voltage dependence of the charge collection current in the junctions, mainly due to drift. In the analysis of digital gates this voltage dependence is unnecessary, since the voltage is either V_{dd} or 0 while the circuit is only sensitive to nmos devices when its drain voltage is high and vice versa. In such circuits, the dependency of collection currents to the signal voltages has become less of a concern. However, since oscillators are large signal, periodic circuits, the collection current is modulated by the oscillation voltage, depending on the amount of and the moment when the charge is injected. When the particle strike occurs when the output signal is small, close to 0 V, the small junction voltage results in only little drift currents in the junctions at the moment of impact. However, when the charge is generated near the peak of the oscillator signal, the reverse junction voltage is large and a large drift current occurs instantaneously.

This phenomenon, combined with the ISF determines the total phase error due to an ionizing particle. Two cases can be distinguished: high and low relative charge collection capability of the junction. In the following subsections it is shown that this effect has a dramatic impact on the collection currents in the oscillator. To get an insight in the problem, simulations are performed in TCAD, modeling a single 65nm CMOS transistor with a minimum gate length and a 5 μm channel width. A heavy-ion particle strike was injected with increasing LET (Linear Energy Transfer) from 10 to 100 $MeV.cm^2/mg$ at various moments in the drain junction. The drain voltage is modulated with a period of 500 ps (2 GHz) and a signal swing from 0 V to 1 V is assumed, as is the case in the practical experiments below. The drain current of the nmos device was used for the analysis below.

A. Low charge generation

In the case of low charge generation, the charge collection capability of the junctions is large compared to the total injected charge. A simulation is shown in Fig. 3 where the instantaneous junction current and accumulated charge is shown. This simulation was done for charge injections at different moments of time. The plot shows an overlay of the collection currents and corresponding collected charges for various injection moments. Each individual curve is the transient current/charge with respect to time. From these simulations it is clear that (1) most charge is collected in a limited amount of time, significantly smaller than the oscillator period (within 100 ps). (2) The total collected charge does not vary significantly with the moment when the charge was injected. Therefore, in this case, the charge injection can be approximated as a current impulse with charge Q :

$$q(t) = Q_{inj} \delta(t - t_{inj}). \quad (6)$$

Since the assumption of linearity in the LTV theory holds, the accumulated phase error can be calculated from (3):

$$\phi = \frac{Q_{inj}}{q_{max}} \Gamma(\omega \cdot t_{inj}) \approx \frac{Q_{inj}}{q_{max}} \cos(\omega \cdot t_{inj}) \quad (7)$$

Depending on the moment of impact, either a positive or negative phase error is expected. The obtained charges from the TCAD simulations (4) can be multiplied with the ideal ISF of the oscillator and integrated to calculate the accumulated phase error of the strike, based on Eqn. 3. This result is shown in Fig. 4 where the instantaneous phase error contribution $d\phi/d\omega t$ and accumulated phase error transient is shown over time, for various injection moments. As expected, the main part of the phase error is induced in the early phase after the charge is generated since most charge is collected instantaneously. Therefore, the simplified model of an impulse current is valid in this case. Some ringing in the phase transient is observed since the current injection decays exponentially and a remaining tail of non-zero current occurs after the first main collection moments, which is multiplied with the periodic ISF function. However, the magnitude can be considered negligible for this analysis. These calculations were done with $q_{max} = 1.55$ pC, based on an LC tank with

Fig. 3: Charge collection current and total collected charge for an LET strike of $10 \text{ MeV.cm}^2/\text{mg}$ for different injection times.

Fig. 4: Instantaneous phase error deviation ($d\phi/dwt$) and total accumulated phase error for an LET strike of $10 \text{ MeV.cm}^2/\text{mg}$ for different injection times.

$L = 1 \text{ nH}$, $C = 3.16 \text{ pF}$ and a voltage amplitude $V_a = 0.5 \text{ V}$ that resonates at 2 GHz .

B. Large charge generation

Previous theory assumed that the charge collection was sufficiently fast to neglect the tail decay and to model the charge collection as an instantaneous pulse. However, when the injected charge is large compared to the junction collection currents, the collection time of the charges may spread across the oscillation period or even multiple periods. As highlighted before, if a particle strike occurs when the junction voltage is minimal, the collection current is relatively small and only little charge is evacuated. Later in time, when the oscillator waveform rises, the charge collection current will increase as well. Therefore, the charge collection is spread over a significant fraction of the period and this current is larger at moments when the voltage is larger. This drastically impacts

Fig. 5: Charge collection current and total collected charge for an LET strike of $100 \text{ MeV.cm}^2/\text{mg}$.

Fig. 6: Instantaneous phase error deviation ($d\phi/dwt$) and total accumulated phase error for an LET strike of $100 \text{ MeV.cm}^2/\text{mg}$.

the overall phase error since the charge collection is pushed to moments when the junction amplitude is larger. As such, if the total generated charge is large, the current due to the particle strike cannot be considered as an impulse current anymore and follows the shape of the waveform dependent junction current.

Similar to the results in Section III-B, Fig. 5 shows the charge collection current and collected charge transients for various injection moments. As explained, limited charge is captured near the minimum, moderate charge is collected near the zero crossings and large amounts are captured near the maximum of the waveform. From the charge collection plot in Fig. 5, it is clear that the majority of the charge collection is delayed until the signal rises which extends up to $1/4^{th}$ of the period in this case. Therefore, the current cannot be modeled as a simple impulse current anymore.

A similar calculation as before in Section III-B can be made by multiplying the collection currents with the ISF and integrating it to find the phase transients, shown in

Fig. 9: Chip photograph.

(a) VCO signal waveform.

(b) Simulated ISF with an ideal $\cos(\omega t)$ ISF function.

Fig. 10: Oscillator characteristics used in the experiments.

this experiment is shown in Fig. 8 and Fig. 9. The circuit is a push-pull oscillator with a supply voltage of 1.2 V and a signal peak value of 1 V. The ratio of pmos to nmos sizes was chosen to balance the ISF to a zero mean value to reduce

Fig. 11: Experimental measurement setup with femto-second Two Photon Laser source, optical photo diode for reference timing and laser injection to VCO.

1/f noise upconversion. The simulated signal waveform and the simulated ISF of the oscillator is shown in Fig. 10a and Fig. 10b. Note that the VCO was succeeded by a differential 50Ω driver such that the on-chip waveform cannot directly be measured.

To accurately correlate injection times of the charges with the measurements, a Two Photon Absorption laser setup was used [23]. One of the main challenges in this measurement setup is the detection of the arrival time of the laser pulse on the chip. Fig. 11 shows the experimental setup. The laser source repetitively emits pulses at a rate of 100 Hz. A fraction of each pulse is split and captured by a photodiode to synchronize the measurements with the phase of the oscillator, while the main beam is injected to the ASIC where the TPA mechanism generates the charges in the silicon substrate [23]. Since the laser trigger is not synchronized with the oscillator, each pulse is injected at a random moment in time with respect to the phase of the oscillator.

B. Measurement results

During each measurement, the oscillator waveform and the photodiode pulse are captured by a high-speed sampling oscilloscope, triggered by the photodiode pulse. For each sample, the time difference between the photodiode pulse and the VCO phase before laser injection is measured to define the arrival time of the laser pulse on the chip with respect to the VCO signal. The accumulated phase error due to the laser pulse is measured by averaging the VCO phase before the laser pulse and extrapolating this after the pulse to measure the absolute phase error. These two measurements from each sample result in a single coordinate in the ISF plot, as shown in fig. 12a and 12b. By taking sufficient samples, pulses are injected at a uniform range in a period of the oscillator. These measurements were done with laser energies of 1.4 nJ and 2.8 nJ respectively. Each circle represent a single laser injection at a random moment in time. In total, 1000 waveforms were captured. Though the noise, generated in the photodiode and its amplifier has an impact on the accuracy of the measurement, a < 2 ps accuracy was achieved in this

(a) Measured phase error across injection times for low charge density injections. Two identical periods are shown.

(b) Measured phase error across injection times for large charge density injections. Two identical periods are shown.

Fig. 12: Measured time dependent phase error as function of injection moment with respect to the oscillator's zero crossing.

setup. Note that, to increase visibility of the measurement, two periods (4π) are shown in Fig. 12. The data shown in the second period is identical to the first. These measurements clearly indicate the time-dependence of the radiation effects on the oscillator. When the charge was injected near zero-crossings, the phase deviation is maximal. Near the maximum of the waveform, the accumulated phase deviation is zero. The measurements showed a clear periodic behavior as expected from the calculations. To achieve a < 2 ps accuracy, a high-speed digital sampling oscilloscope with 40 GSa/s and 13 GHz bandwidth was used that has an internal jitter < 200 fs. The oscillator itself has a cycle-to-cycle jitter of only 6 fs, calculated from phase-noise measurements [24]. The remaining timing-uncertainty originates from the photodiode and amplifier noise.

V. CONCLUSION

A general theory on Single Event Transients on integrated CMOS LC-oscillators was presented in this article. The periodic Impulse Sensitive Function of the oscillator was used to model the time dependent effects of injected charges. It was shown, using TCAD simulations, that the Single Event Transient junction currents magnitude is highly dependent on the junction voltage which is modulated by the oscillator waveform. This has a severe impact with large charge densities and when injected charges cannot be evacuated in a fraction of the oscillation period. An experimental verification was done that proves the time dependent radiation effects using a Two Photon Absorption experiment.

REFERENCES

- [1] C. Zhang et al., "Characterization of GigaRad Total Ionizing Dose and Annealing Effects on 28-nm Bulk MOSFETs," *IEEE Trans. Nucl. Sci.*, vol. 64, no. 10, pp. 2639-2647, Oct. 2017.
- [2] G. Gorine et al., "Ultrahigh Fluence Radiation Monitoring Technology for the Future Circular Collider at CERN," *IEEE Trans. Nucl. Sci.*, vol. 65, no. 8, pp. 1583-1590, Aug. 2018.
- [3] V. Ferlet-Cavrois, L. W. Massengill and P. Gouker, "Single Event Transients in Digital CMOS—A Review," *IEEE Trans. Nucl. Sci.*, vol. 60, no. 3, pp. 1767-1790, June 2013.
- [4] P.E. Dodd, L.W. Massengill, "Basic mechanisms and modeling of single-event upset in digital microelectronics," *IEEE Trans. Nucl. Sci.*, vol. 50, no. 3, pp. 583 - 602, July 2003.
- [5] J. M. Benedetto, P. H. Eaton, D. G. Mavis, M. Gadlage and T. Turflinger, "Digital Single Event Transient Trends With Technology Node Scaling," *IEEE Trans. Nucl. Sci.*, vol. 53, no. 6, pp. 3462-3465, Dec. 2006.
- [6] T. D. Loveless, L. W. Massengill, W. T. Holman and B. L. Bhuva, "Modeling and Mitigating Single-Event Transients in Voltage-Controlled Oscillators," *IEEE Trans. Nucl. Sci.*, vol. 54, no. 6, pp. 2561-2567, Dec. 2007.
- [7] T. D. Loveless et al., "A Probabilistic Analysis Technique Applied to a Radiation-Hardened-by-Design Voltage-Controlled Oscillator for Mixed-Signal Phase-Locked Loops," *IEEE Trans. Nucl. Sci.*, vol. 55, no. 6, pp. 3447-3455, Dec. 2008.
- [8] L. Chen, X. Wen, Y. You, D. Huang, C. Li and J. Chen, "A radiation-tolerant ring oscillator phase-locked loop in $0.13\mu\text{m}$ CMOS," *Proc. International Midwest Symposium on Circuits and Systems (MWSCAS)*, 2012, pp. 13-16.
- [9] Y. Boulghassoul, L. W. Massengill, A. L. Sternberg, B. L. Bhuva and W. T. Holman, "Towards SET Mitigation in RF Digital PLLs: From Error Characterization to Radiation Hardening Considerations," *IEEE Trans. Nucl. Sci.*, vol. 53, no. 4, pp. 2047-2053, Aug. 2006.
- [10] H. H. Chung, W. Chen, B. Bakkaloglu, H. J. Barnaby, B. Vermeire and S. Kiaei, "Analysis of Single Events Effects on Monolithic PLL Frequency Synthesizers," *IEEE Trans. Nucl. Sci.*, vol. 53, no. 6, pp. 3539-3543, Dec. 2006.
- [11] T. D. Loveless, L. W. Massengill, W. T. Holman, B. L. Bhuva, D. McMorrow and J. H. Warner, "A Generalized Linear Model for Single Event Transient Propagation in Phase-Locked Loops," *IEEE Trans. Nucl. Sci.*, vol. 57, no. 5, pp. 2933-2947, Oct. 2010.
- [12] Z. Zhenyu, Z. Minxuan, C. Jihua and Guo Bin, "A single-event transient hardened phase-locked loop in $0.18\mu\text{m}$ CMOS process," *Proc. International Conference on ASIC*, 2009, pp. 284-287.
- [13] Loveless TD et al. "A hardened-by-design technique for RF digital phase-locked loops". *IEEE Trans. Nucl. Sci.*, vol. 53 no. 6, pp 3432-3438, Dec. 2006.
- [14] T. Wang, K. Wang, L. Chen, A. Dinh, B. Bhuva and R. Shuler, "A RHBD LC-Tank Oscillator Design Tolerant to Single-Event Transients," *IEEE Trans. Nucl. Sci.*, vol. 57, no. 6, pp. 3620-3625, Dec. 2010.
- [15] Y. Gao, J. Lou, J. Zhang, L. Li and F. Xu, "Single-event transients in LC-tank VCO," *Proc. Int. Workshop on Microwave and Millimeter Wave Circ. and Syst. Tech.*, 2012: doi: 10.1109/MMWCST.2012.6238178.
- [16] Z. Zhang, L. Chen and H. Djahanshahi, "A Hardened-By-Design Technique for LC-Tank Voltage Controlled Oscillator," *Proc. Canadian Conf. on Elec. & Comput. Eng. (CCECE)*, 2018: doi: 10.1109/CCECE.2018.8447659.

- [17] J. Prinzie, J. Christiansen, P. Moreira, M. Steyaert and P. Leroux, "A 2.56-GHz SEU Radiation Hard LC-Tank VCO for High-Speed Communication Links in 65-nm CMOS Technology," *IEEE Trans. Nucl. Sci.*, vol. 65, no. 1, pp. 407-412, Jan. 2018.
- [18] S. J. Horst, S. D. Phillips, P. Saha, J. D. Cressler, D. McMorrow and P. Marshall, "A Theory of Single-Event Transient Response in Cross-Coupled Negative Resistance Oscillators," *IEEE Trans. Nucl. Sci.*, vol. 57, no. 6, pp. 3349-3357, Dec. 2010.
- [19] W. Chen et al., "Impact of VCO Topology on SET Induced Frequency Response," *IEEE Trans. Nucl. Sci.*, vol. 54, no. 6, pp. 2500-2505, Dec. 2007.
- [20] S. E. Armstrong, T. D. Loveless, J. R. Hicks, W. T. Holman, D. McMorrow and L. W. Massengill, "Phase-Dependent Single-Event Sensitivity Analysis of High-Speed A/MS Circuits Extracted from Asynchronous Measurements," *IEEE Trans. Nucl. Sci.*, vol. 58, no. 3, pp. 1066-1071, Jun. 2011.
- [21] A. Hajimiri and T. H. Lee, "Design issues in CMOS differential LC oscillators," *IEEE J. Solid-State Circ.*, vol. 34, no. 5, pp. 717-724, May 1999.
- [22] A. Hajimiri and T. H. Lee, "A general theory of phase noise in electrical oscillators," *IEEE J. Solid-State Circ.*, vol. 33, no. 2, pp. 179-194, Feb. 1998.
- [23] D. McMorrow et al., "Three-dimensional mapping of single-event effects using two photon absorption," *IEEE Trans. Nucl. Sci.*, vol. 50, no. 6, pp. 2199-2207, Dec. 2003.
- [24] J. Prinzie, M. Steyaert, P. Leroux, J. Christiansen and P. Moreira, "A single-event upset robust, 2.2 GHz to 3.2 GHz, 345 fs jitter PLL with triple-modular redundant phase detector in 65 nm CMOS," *Proc. IEEE Asian Solid-State Circ. Conf. (ASSCC)*, 2016, pp. 285-288.