Dual-MEMS-Resonator Temperature-to-Digital Converter with 40μK Resolution and FOM of 0.12pJK²

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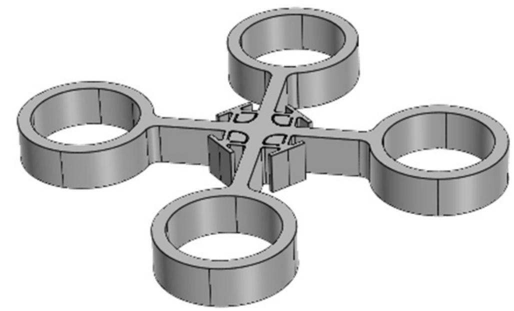
Precision Oscillator Applications

±1ppm - ±10ppm

±0.01ppm - ±1ppm

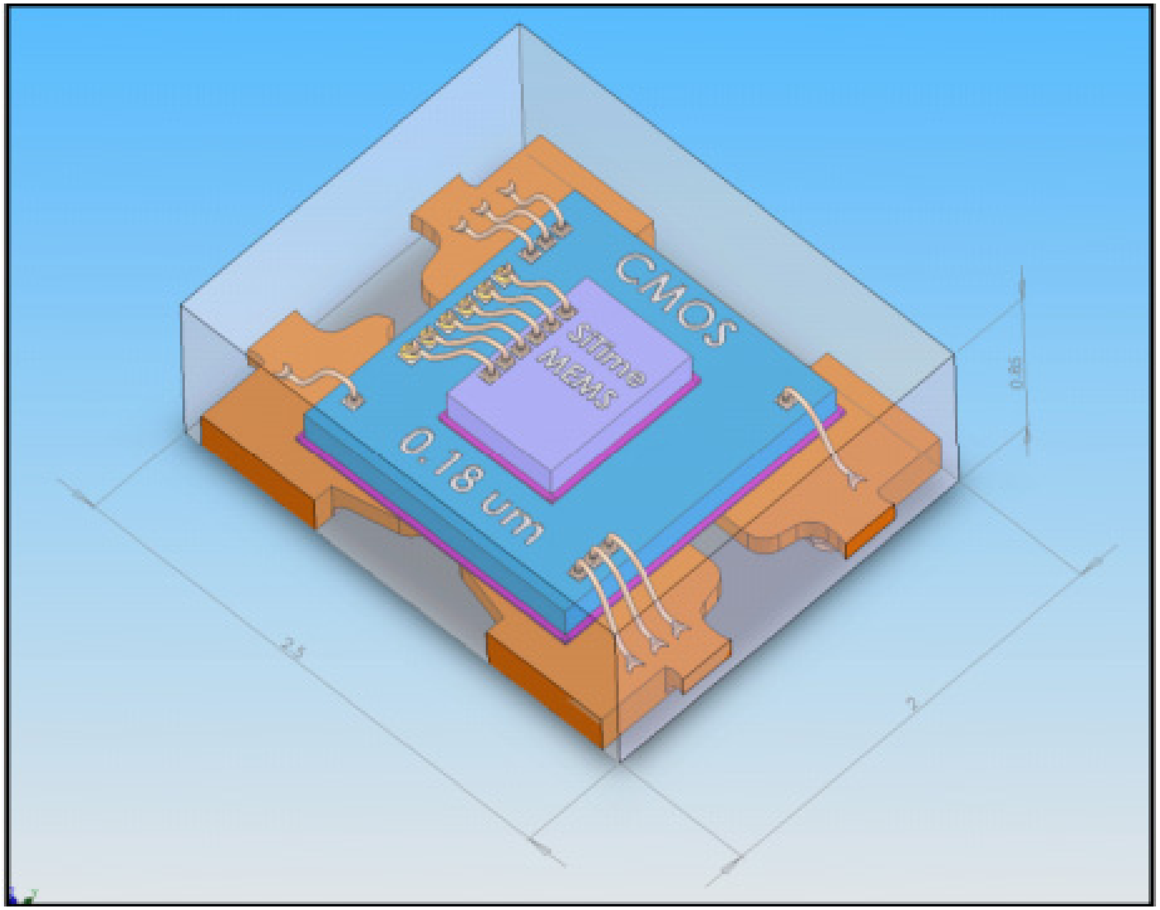
±0.5ppm

Precision Oscillator Resonators



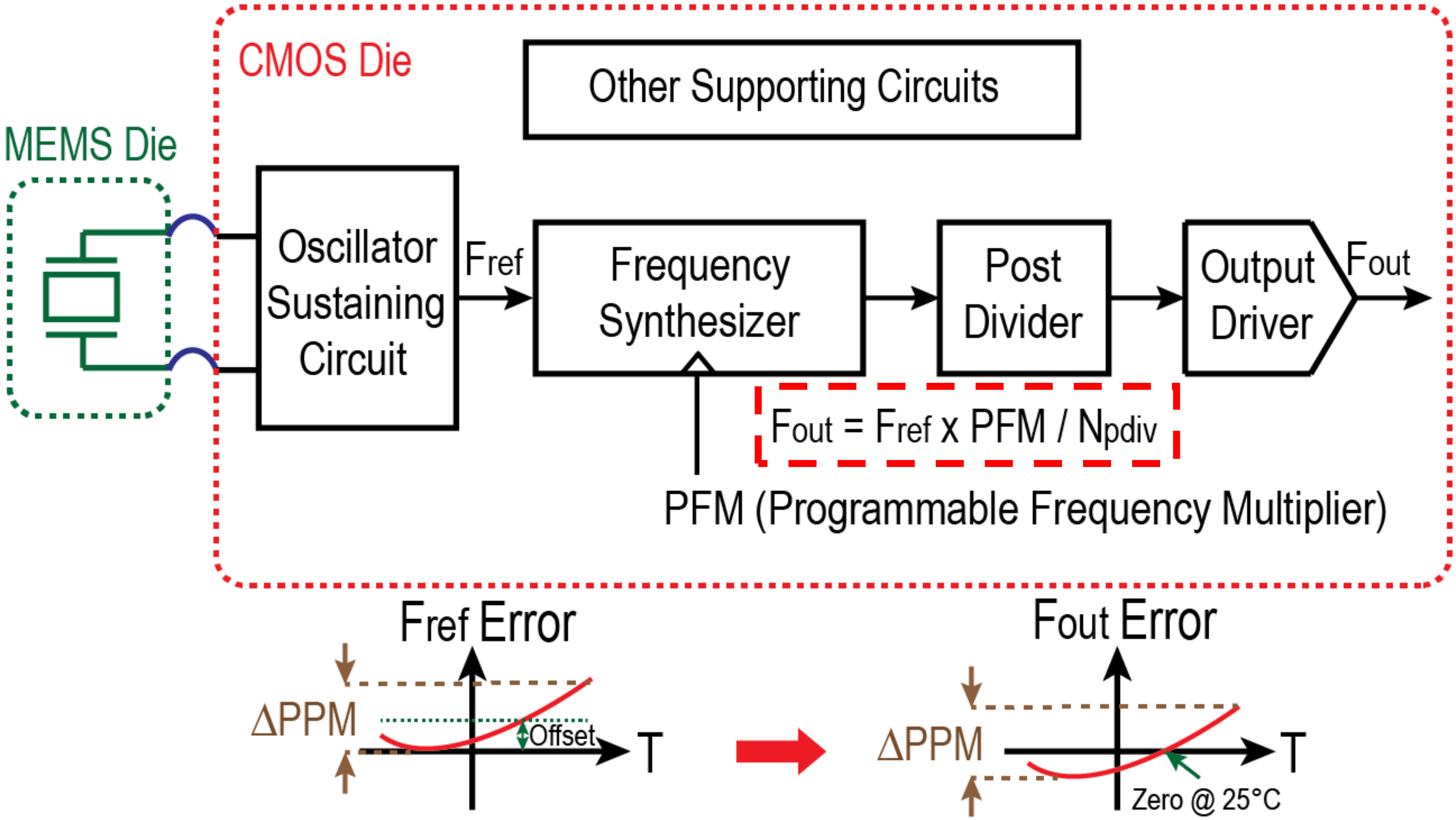
Parameter	Quartz	MEMS
Quality Factor	High	High
Stability	High	High
Fabrication	Dedicated Manufacturing Process	Leverages Semiconductor Process
Performance Against Shock and Vibration	Sensitive	Robust
Vacuum Seal	Package	Die

MEMS-Based Programmable Oscillator Package



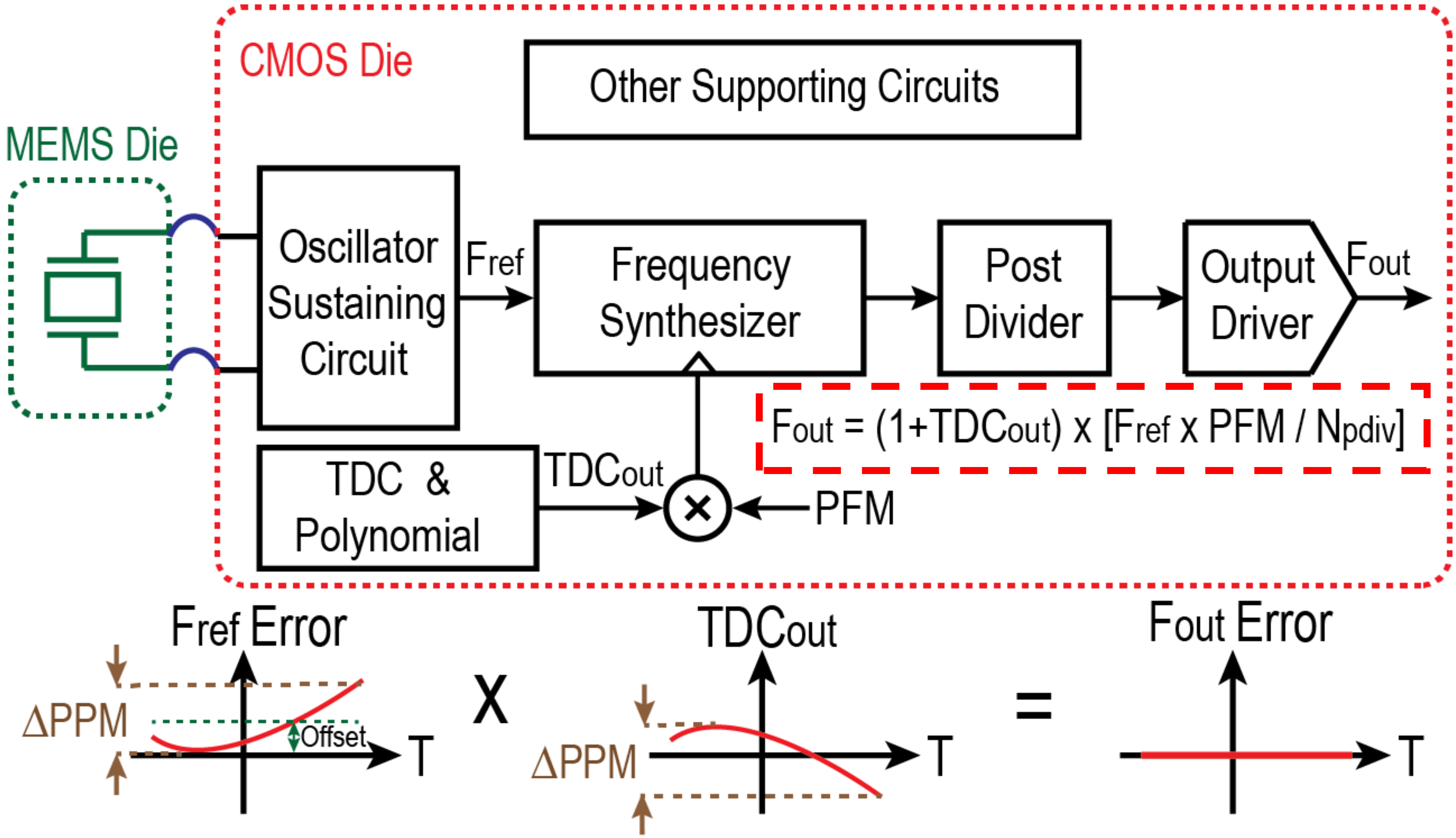
MEMS die, CMOS die and leadframe in a package

MEMS-Based Programmable Oscillator (XO)



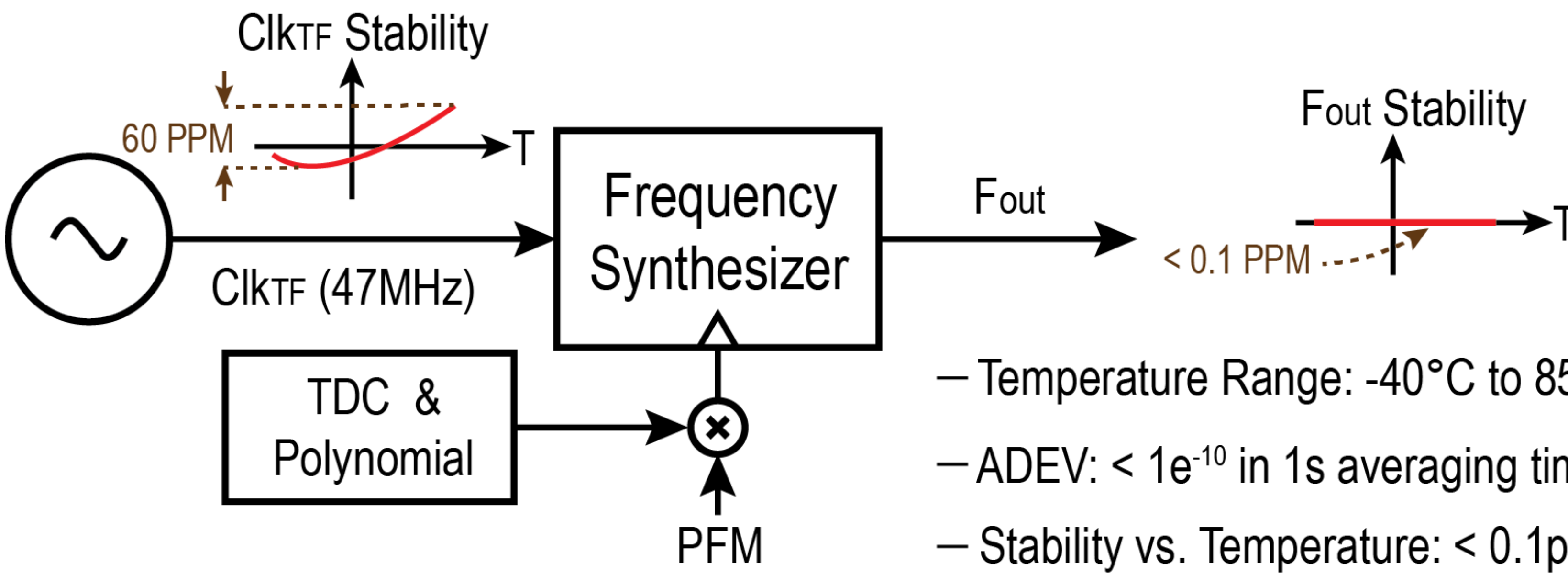
Output stability matches reference resonator

MEMS-Based Programmable Oscillator (TCXO)



Temperature-to-Digital Converter (TDC) is needed

TDC Specifications



- Temperature Range: -40°C to 85°C
- ADEV: < $1e^{-10}$ in 1s averaging time
- Stability vs. Temperature: < 0.1ppm

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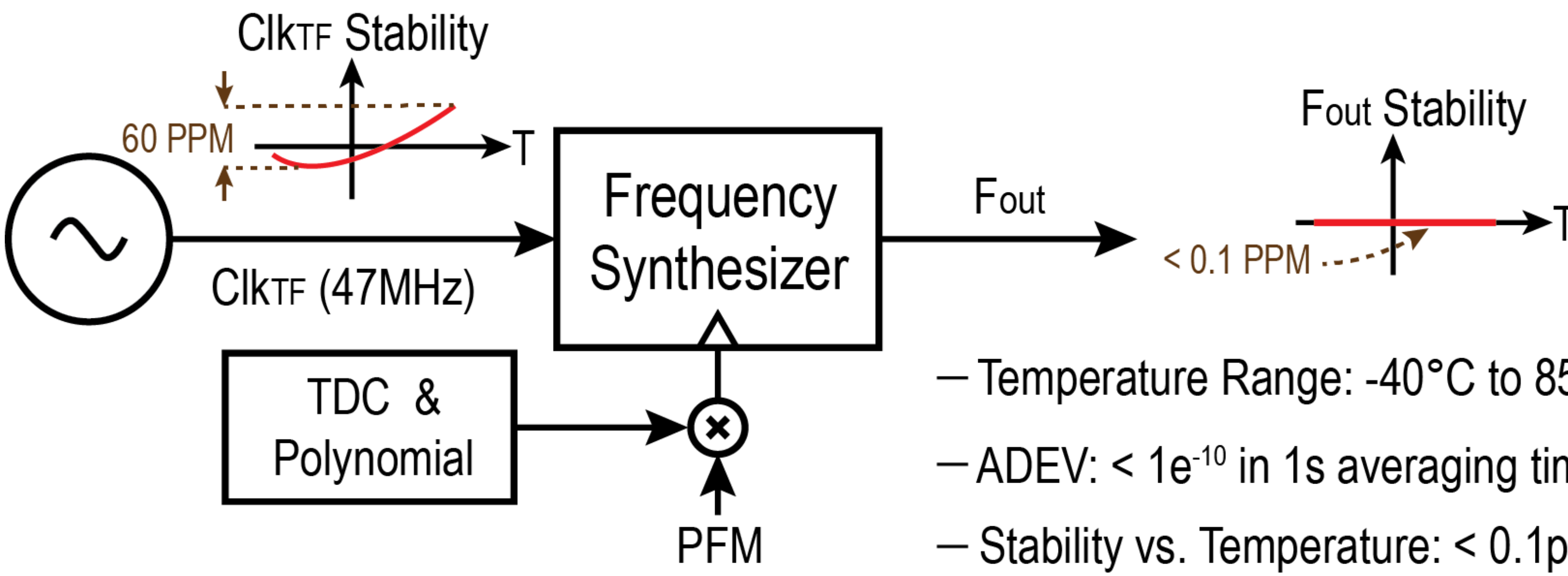


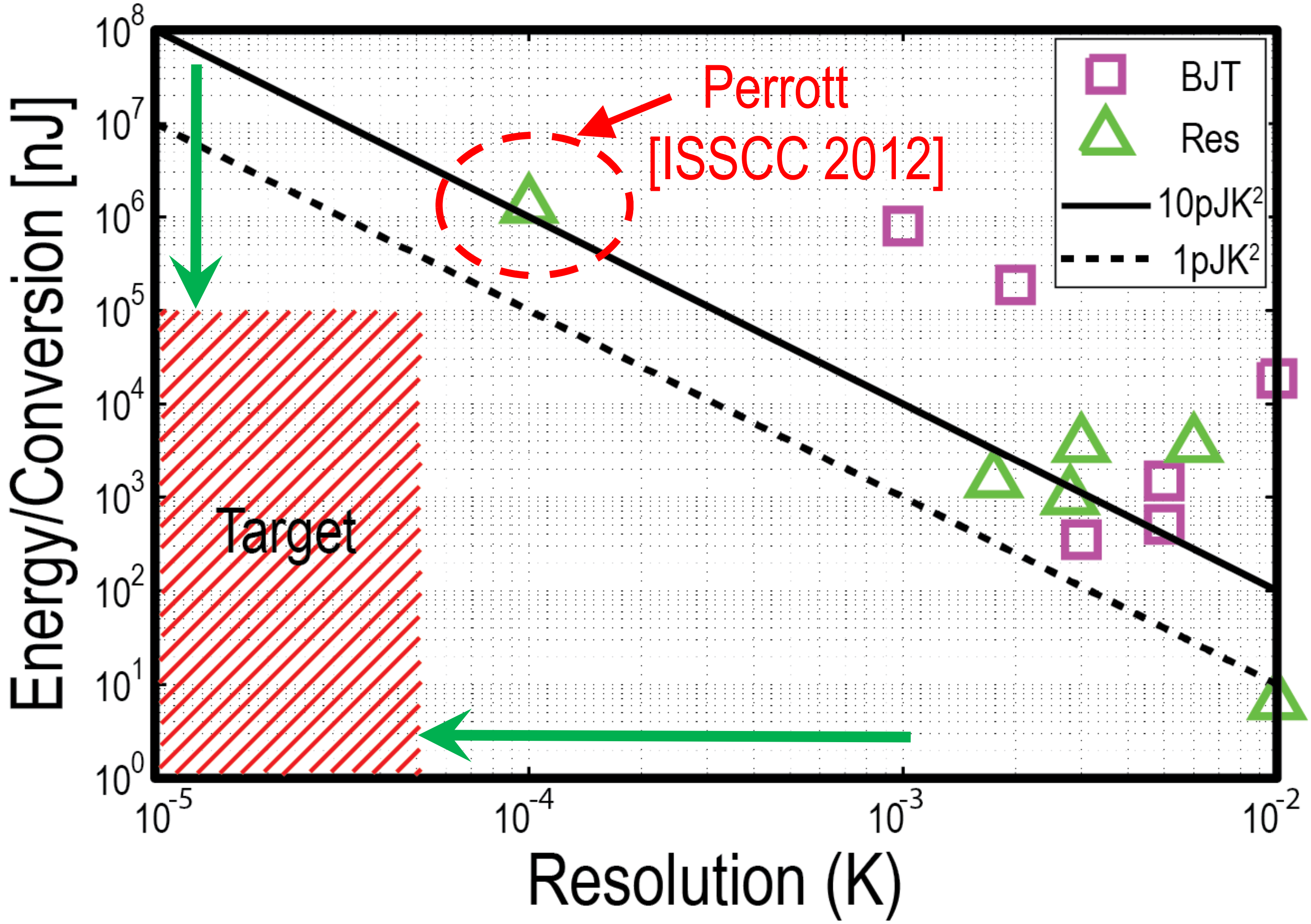
- Temperature Range: -40°C to 85°C
- ADEV: < $1e^{-10}$ in 1s averaging time
- Stability vs. Temperature: < 0.1ppm

Parameter	TDC Spec.	Device Spec.
Power	< 20mW	application demand
Bandwidth (BW)	> 100Hz	maintain ADEV in thermally noisy environment (fan,...)
Resolution	< 0.05mK	ADEV requirement

State-of-the-Art TDCs

	BJT-Based		Resistor-Based		
Parameter	A. Heidary [ISSCC'14]	R. Eitan [JLPEA'14]	M. Perrott [ISSCC'12]	C. H. Weng [JSSC'15]	Target
CMOS Technology	0.07µm	0.02µm	0.18µm	0.18µm	0.18µm
Power Consumption	159µW	1150µW	13mW	64.5µW	< 20mW
Conversion Time	2.2ms	0.02ms	100ms	0.1ms	< 5ms
Resolution	3mK	250mK	0.1mK	10mK	< 0.05mK

Prior Architectures Unsuitable

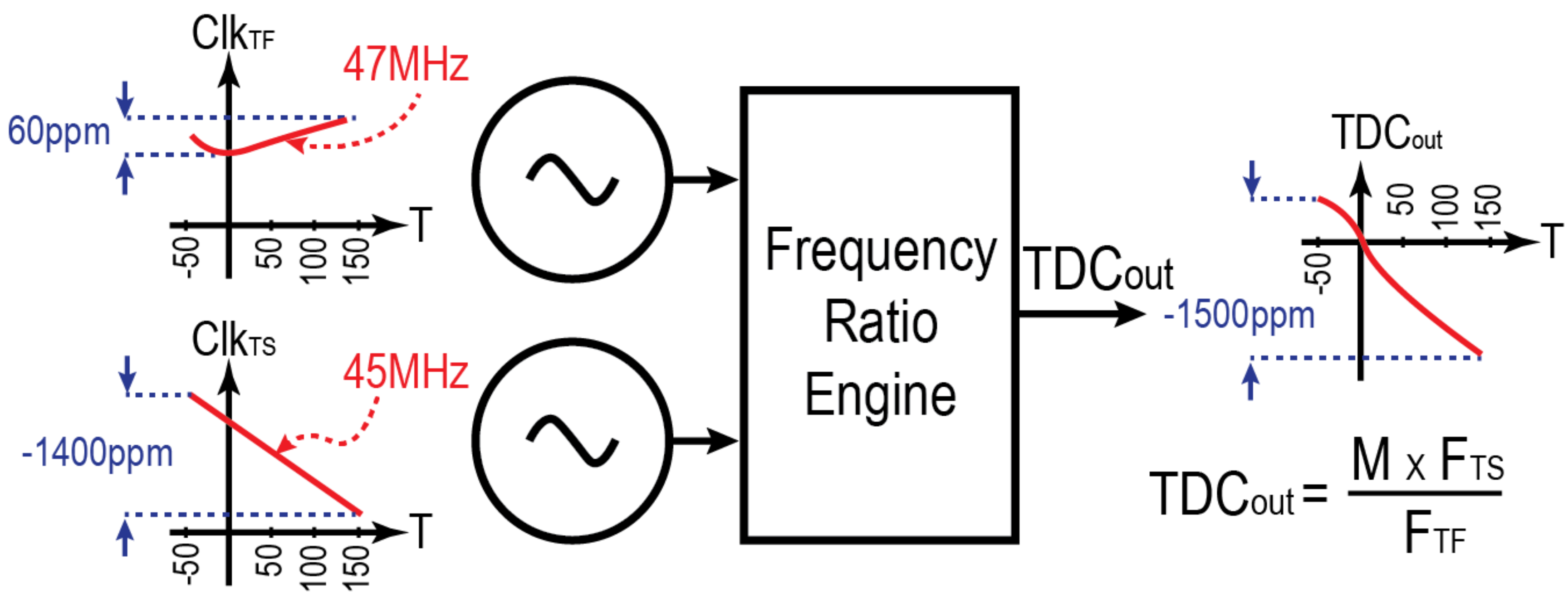


Resolution FOM = (Energy/Conversion)×Resolution^2

K.A.A. Makinwa, "Smart Temperature Sensor Survey", [Online]. Available: http://ei.ewi.tudelft.nl/docs/TSensor_survey.xls

Dual-MEMS Resonator TDC

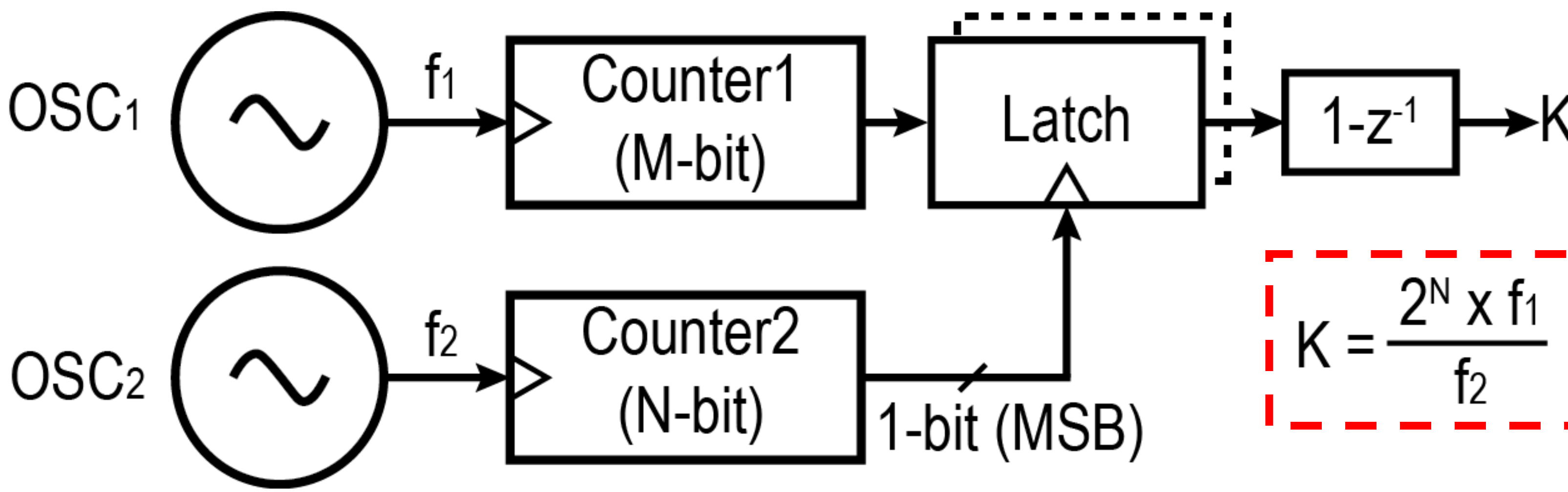
- Different temperature coefficients (TC) for two clocks
  - Frequency ratio indicates temperature
  - TempSense clock (Clk_{TS}): TC = -7ppm/K
  - TempFlat clock(Clk_{TF}): TC < 1ppm/K



$$TDC_{out} = \frac{M \times F_{TS}}{F_{TF}}$$

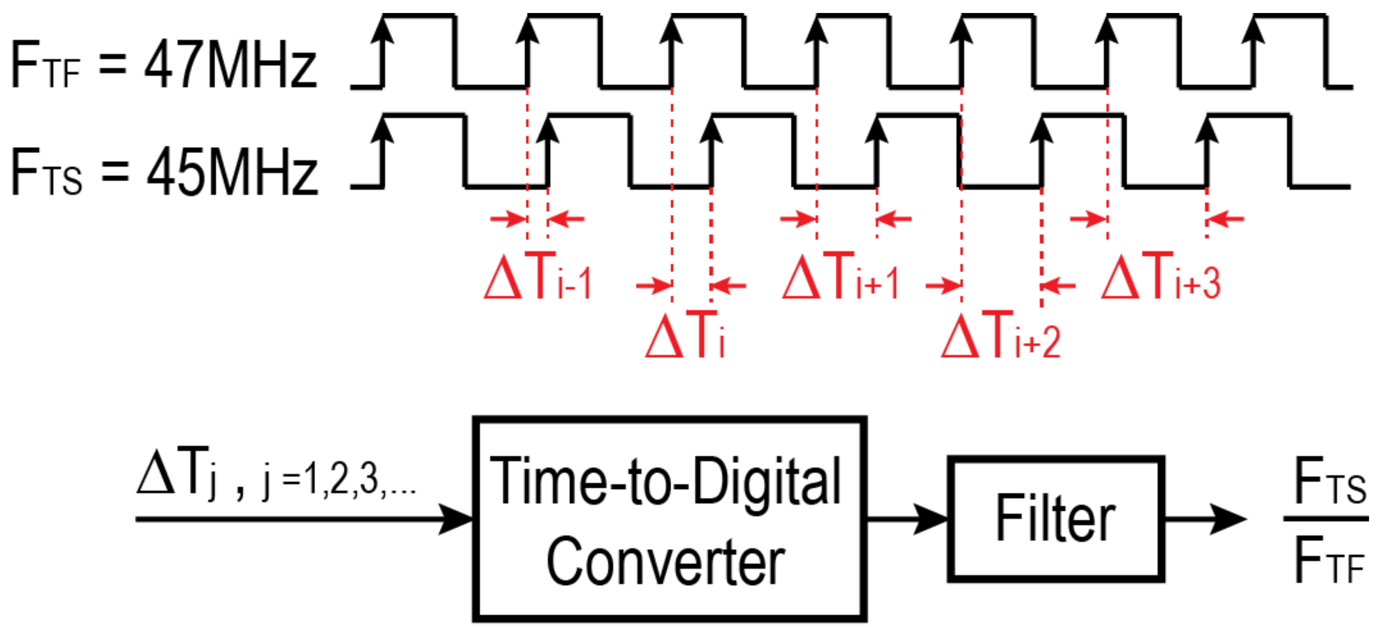
Frequency Ratio Measurement Techniques

- Reciprocal counting method
- Counts OSC_1's number of cycles in a time window set by OSC_2 and counter2



$$K = \frac{2^N \times f_1}{f_2}$$

Proposed Ratio Engine



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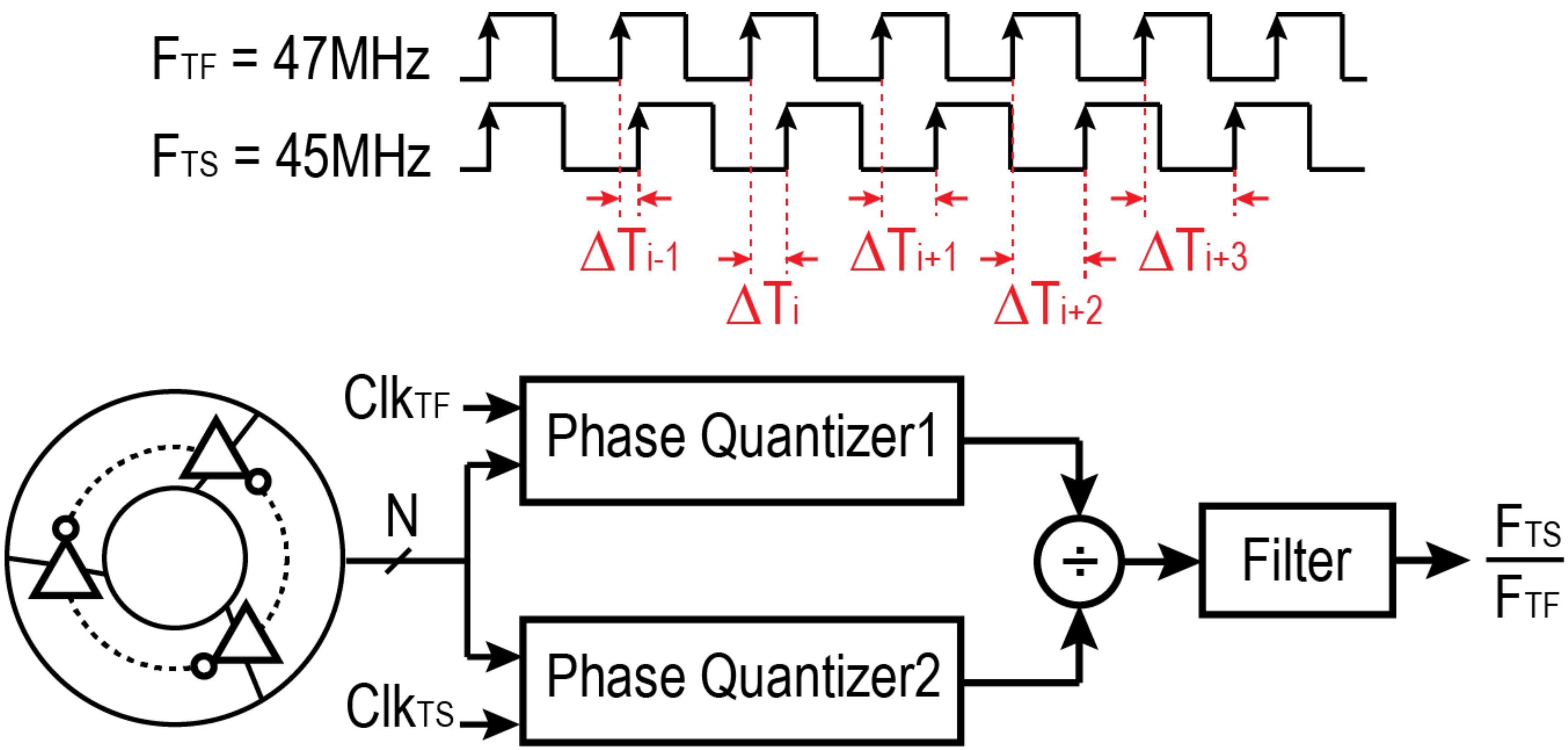

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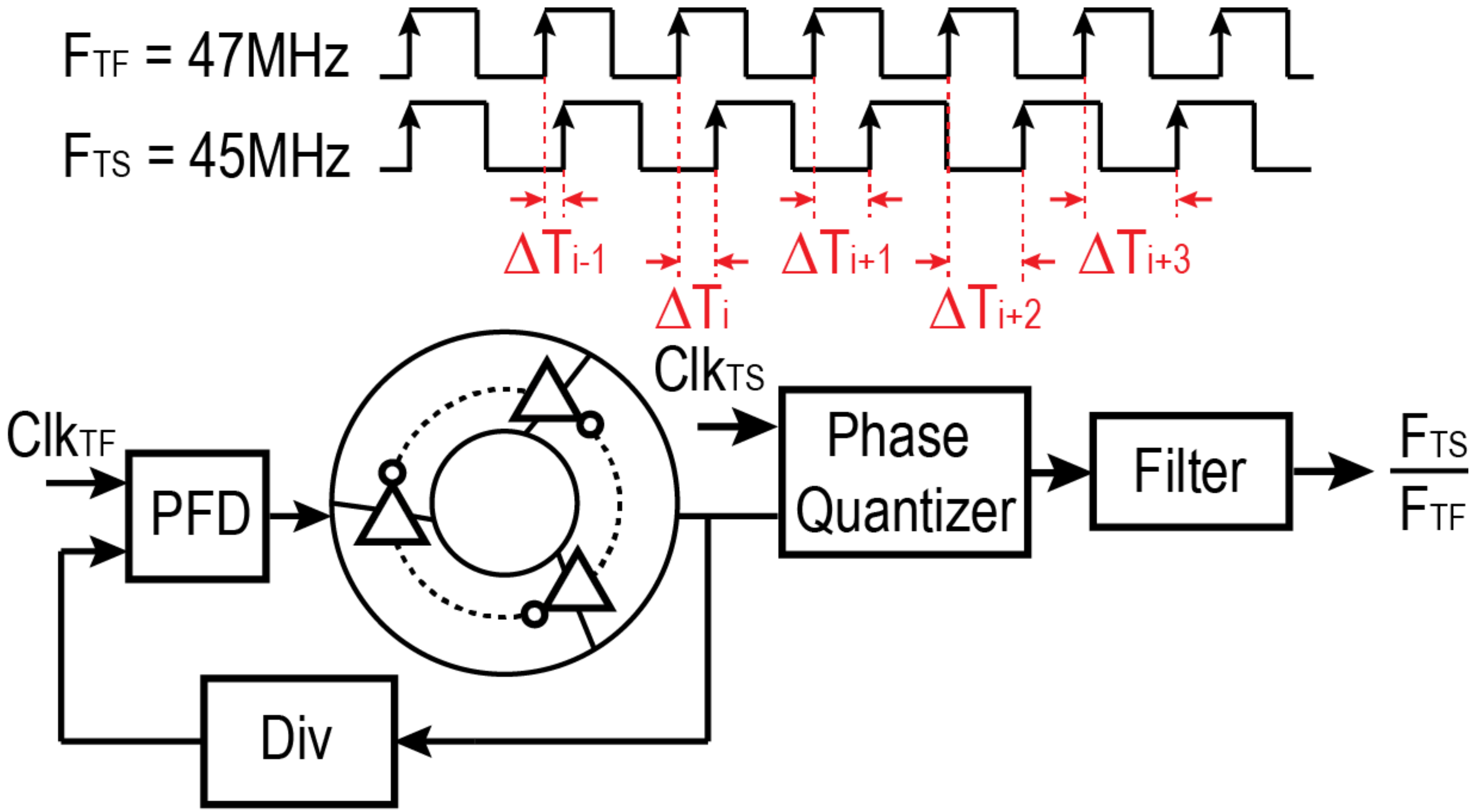
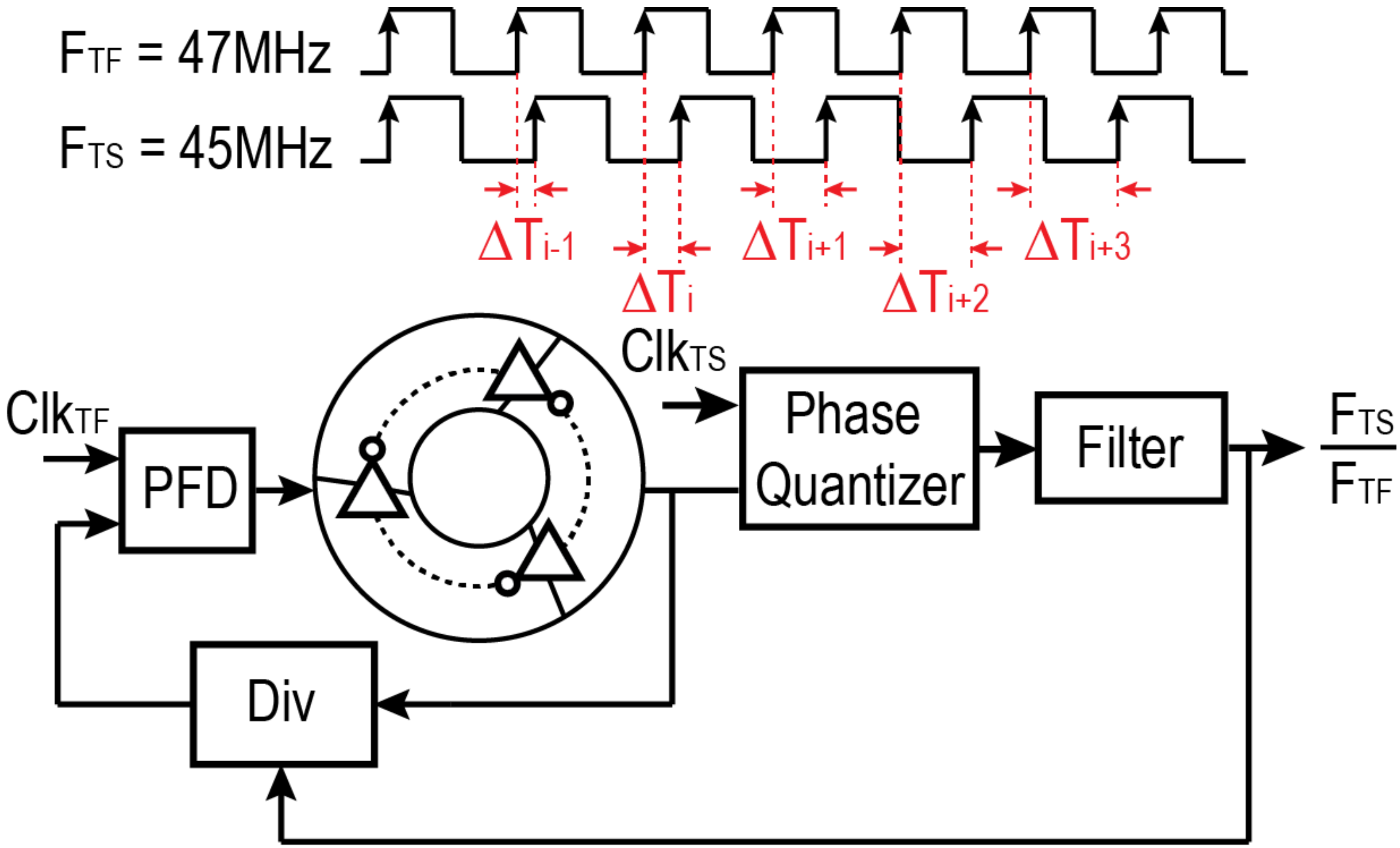
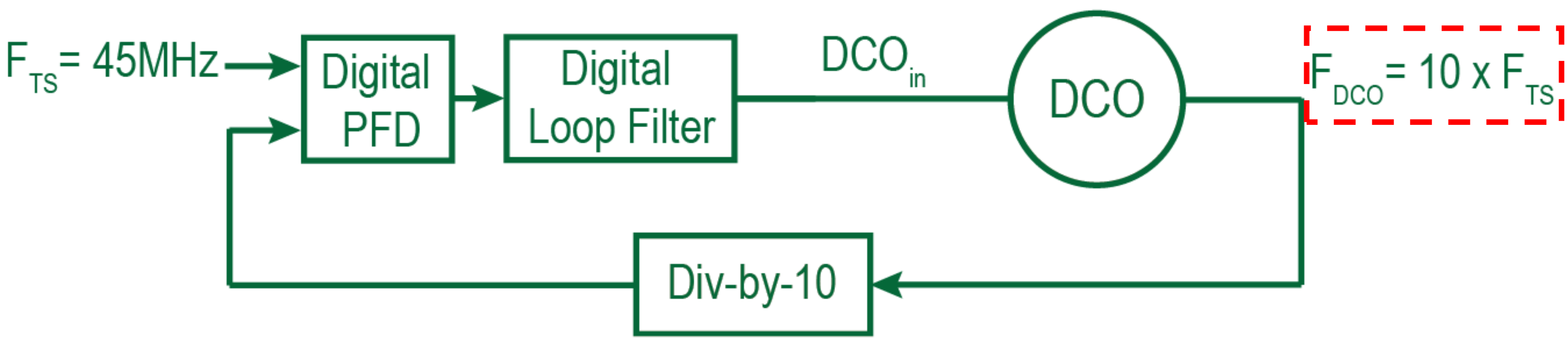


VCO is locked to Clk_{TF}

Proposed Ratio Engine



Implementation Flow



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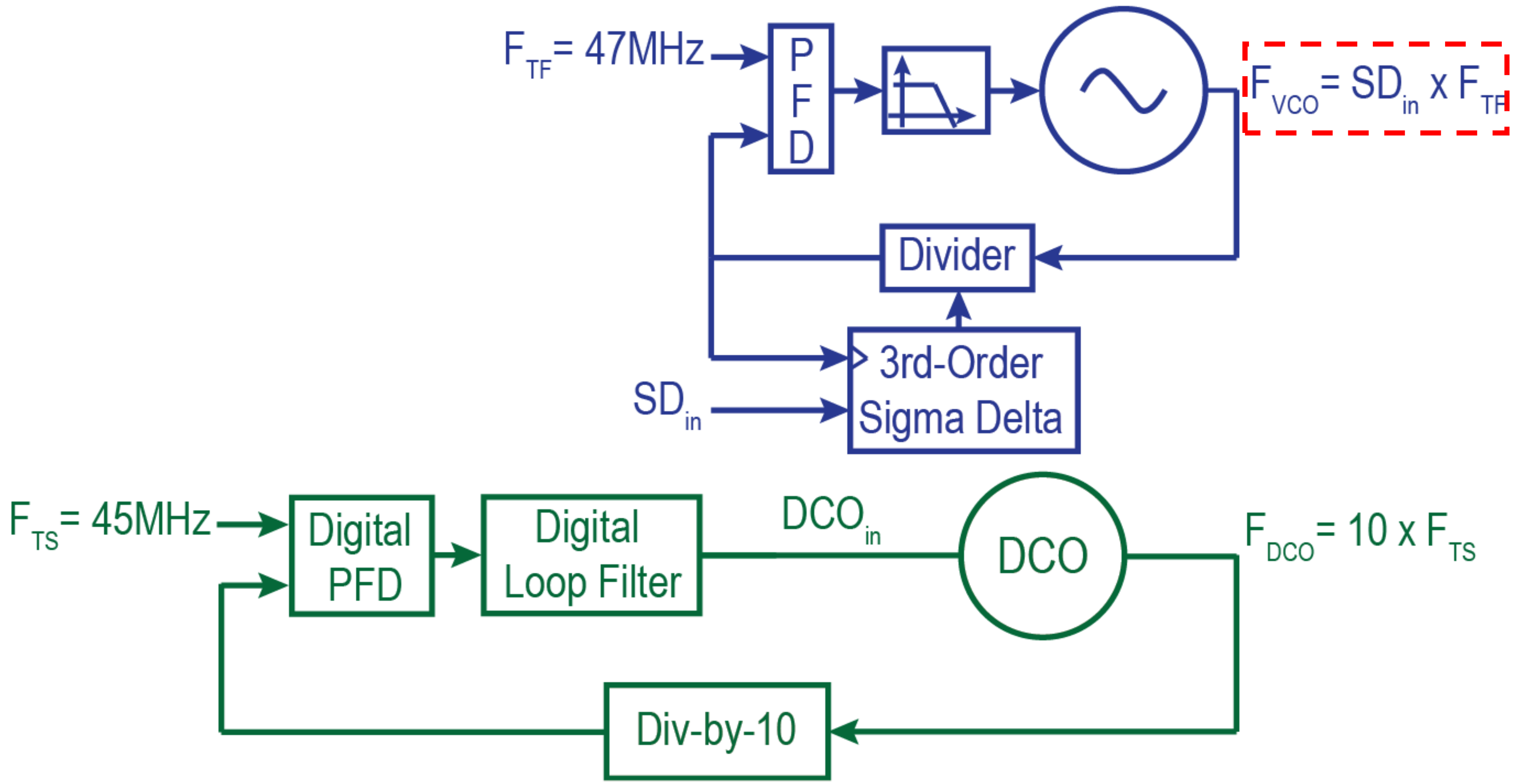

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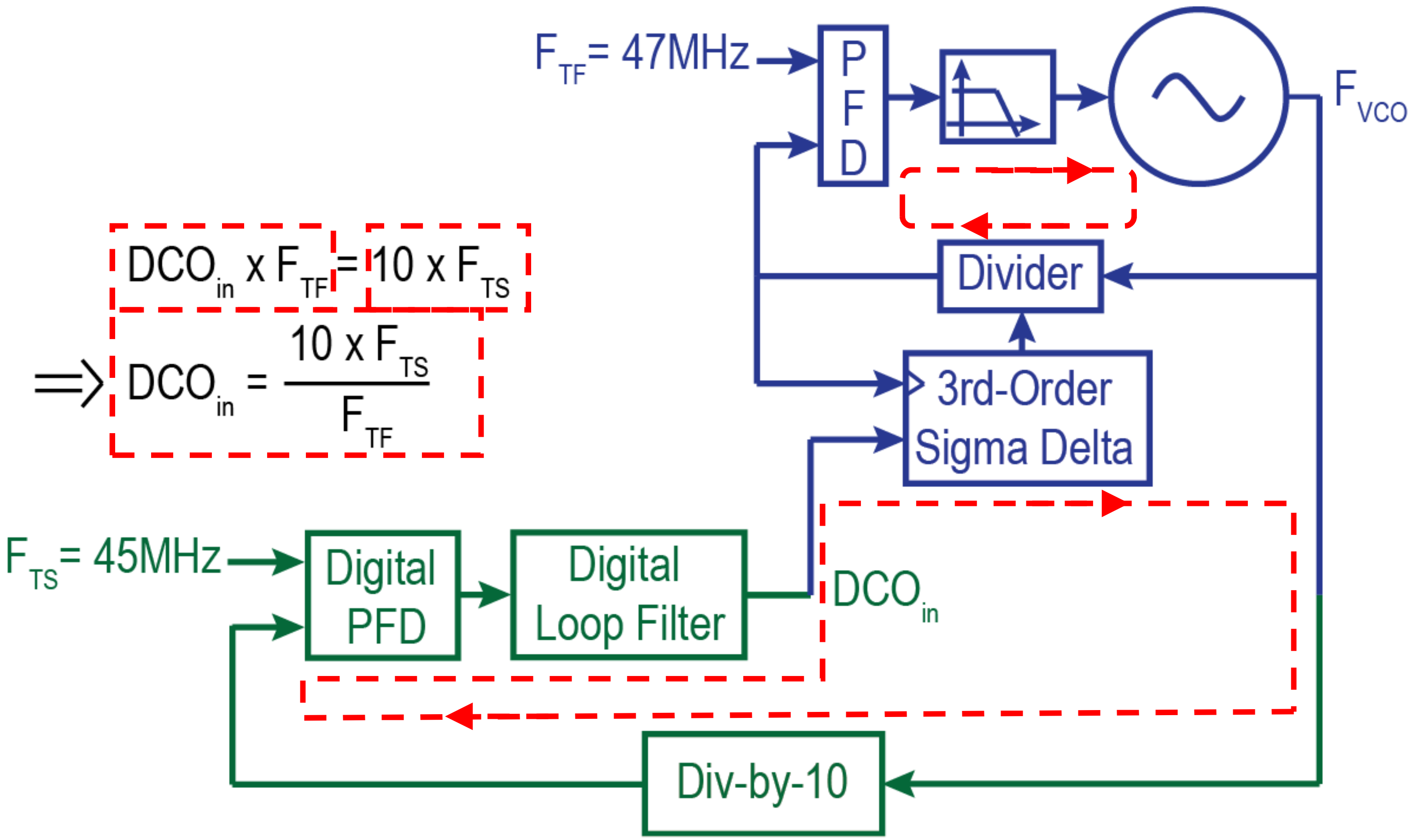

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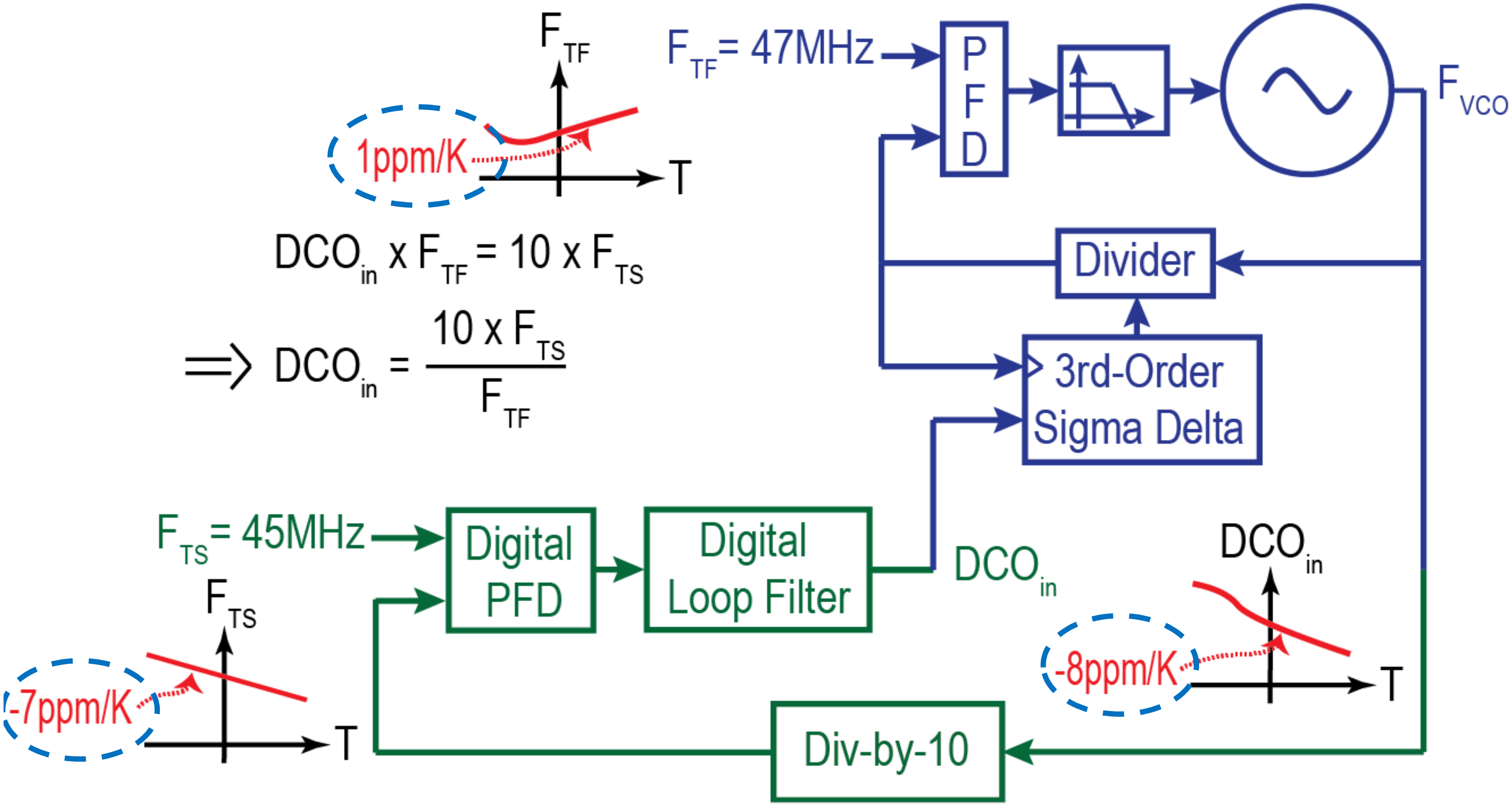
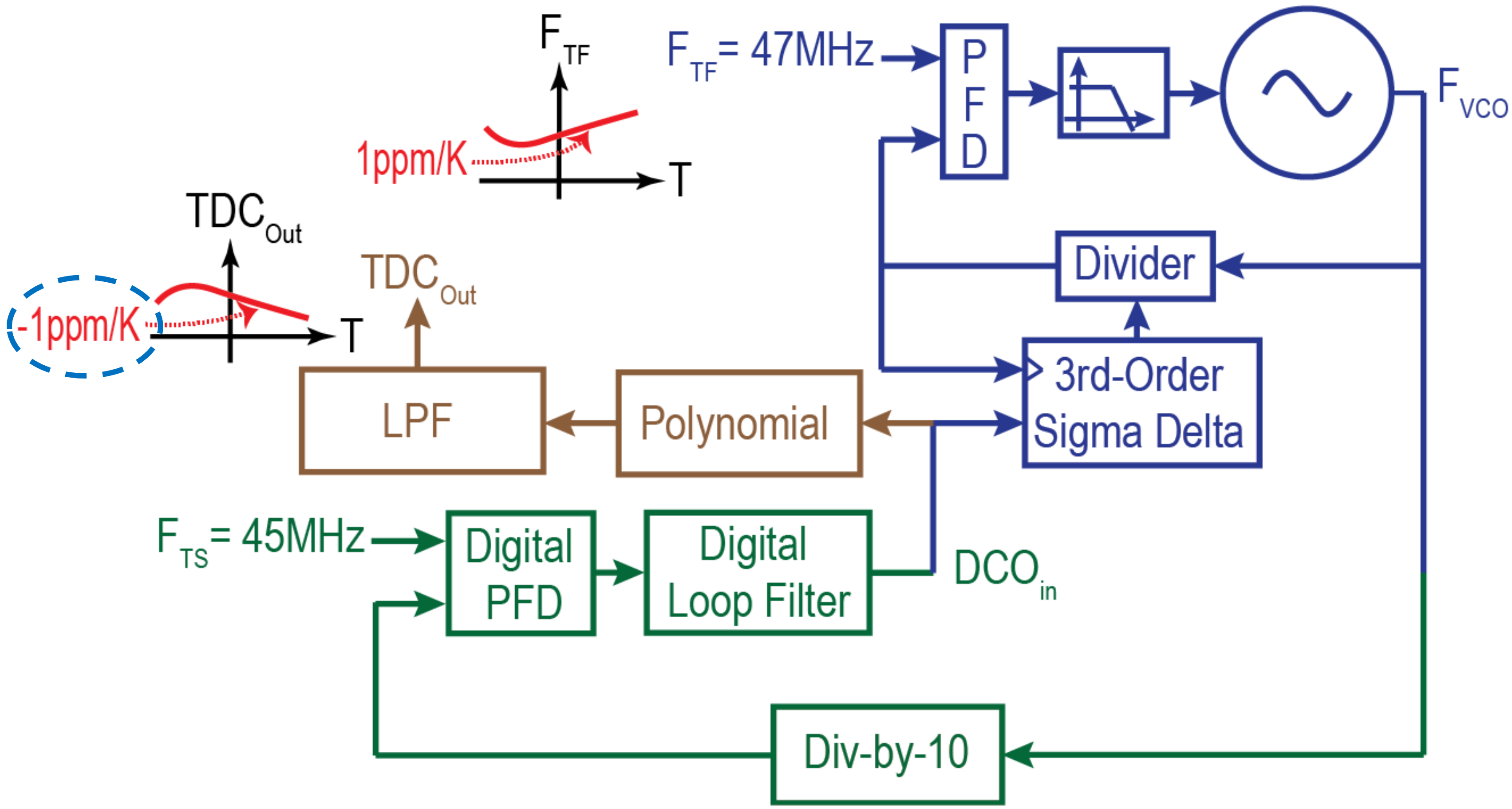


$$DCO_{in} \times F_{TF} = 10 \times F_{TS}$$

$$\Longrightarrow DCO_{in} = \frac{10 \times F_{TS}}{F_{TF}}$$

Implementation Flow



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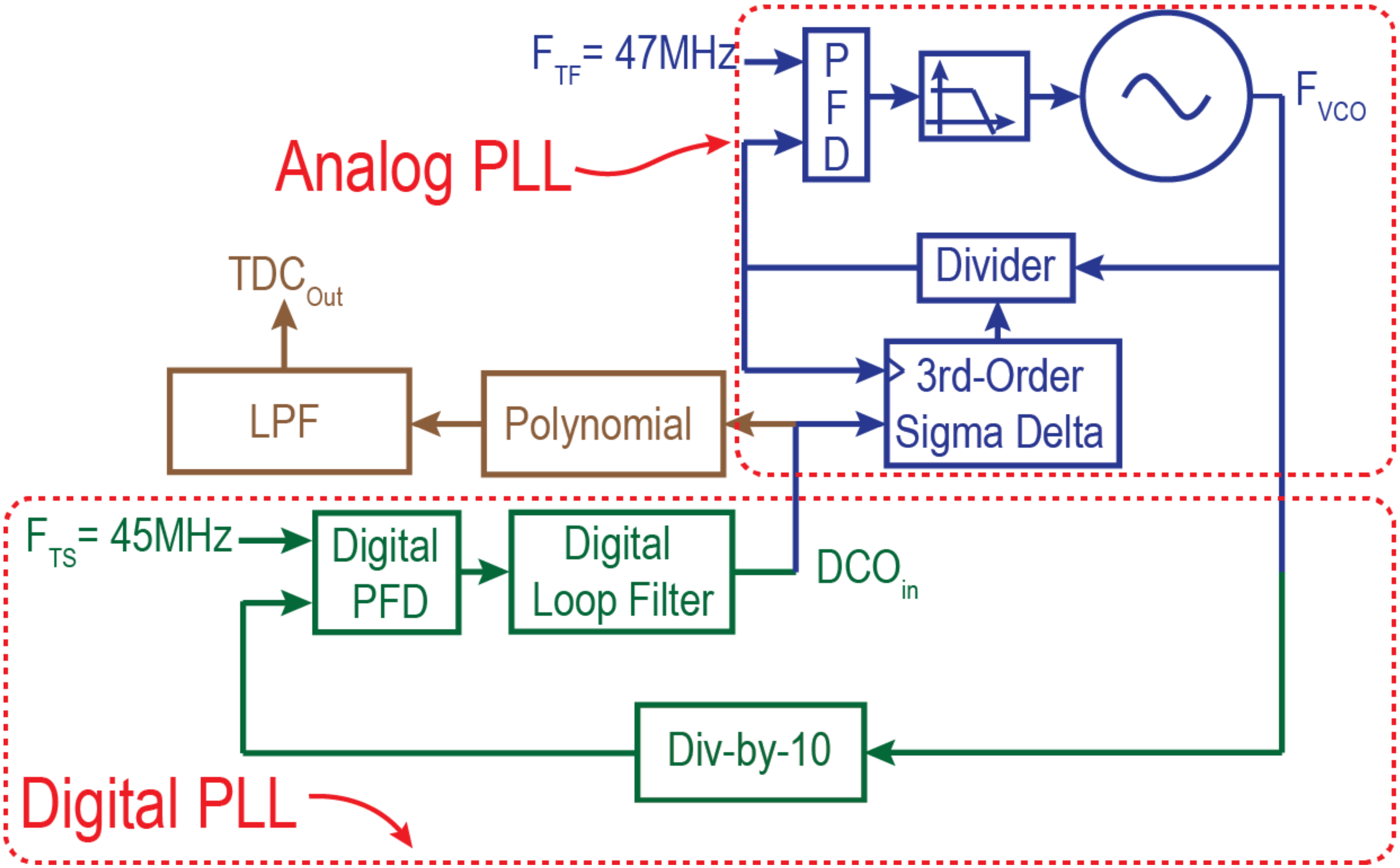
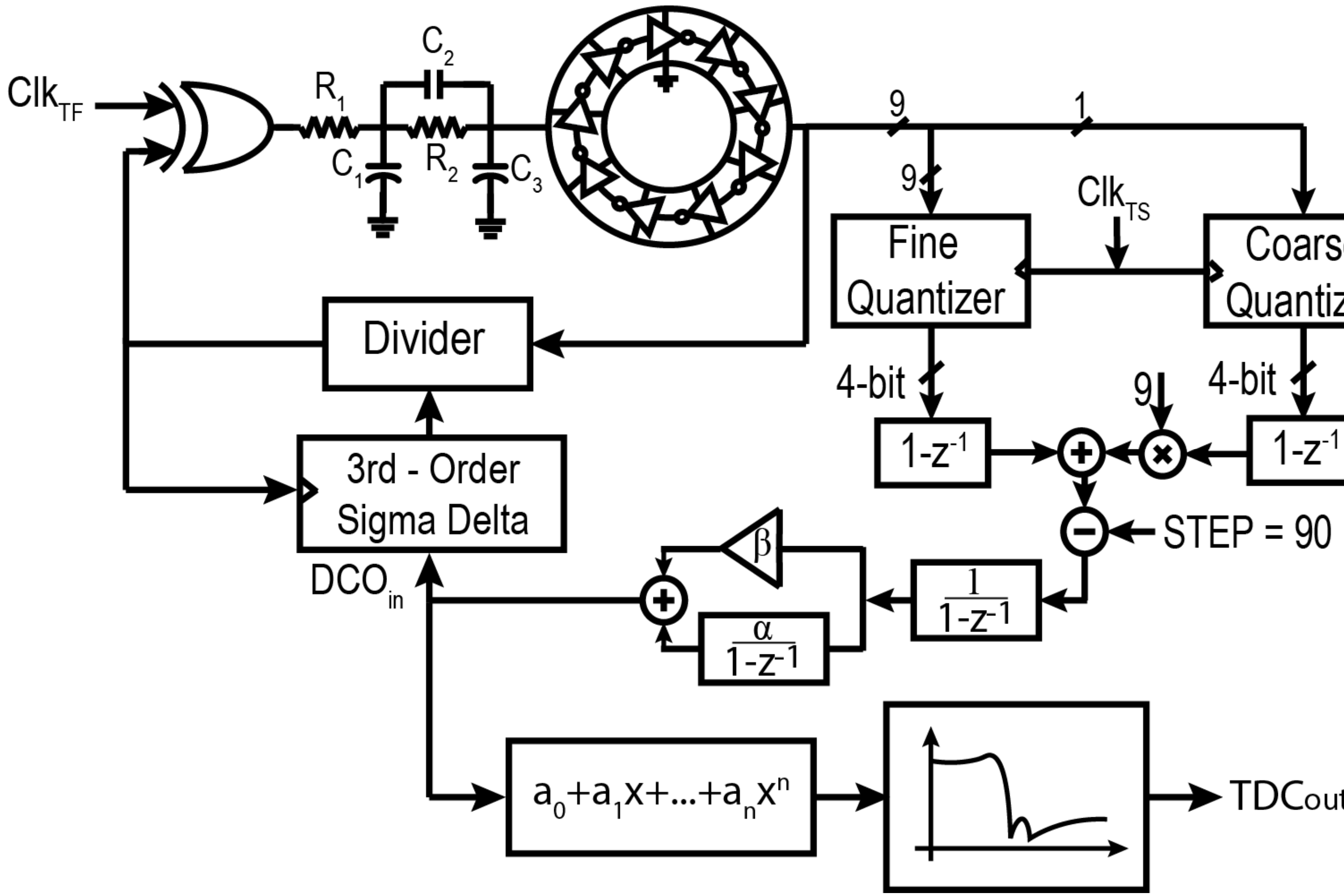


More Details



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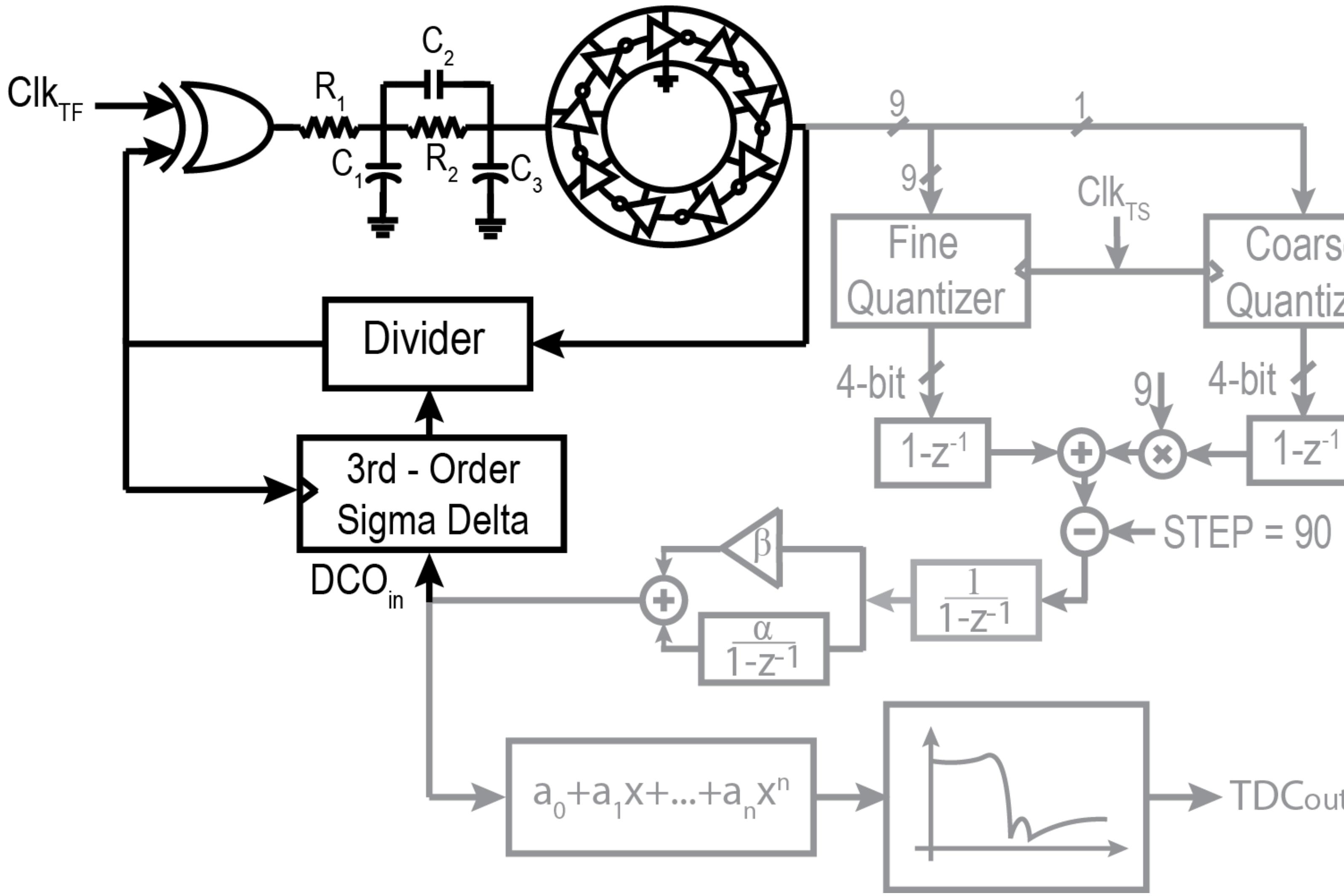

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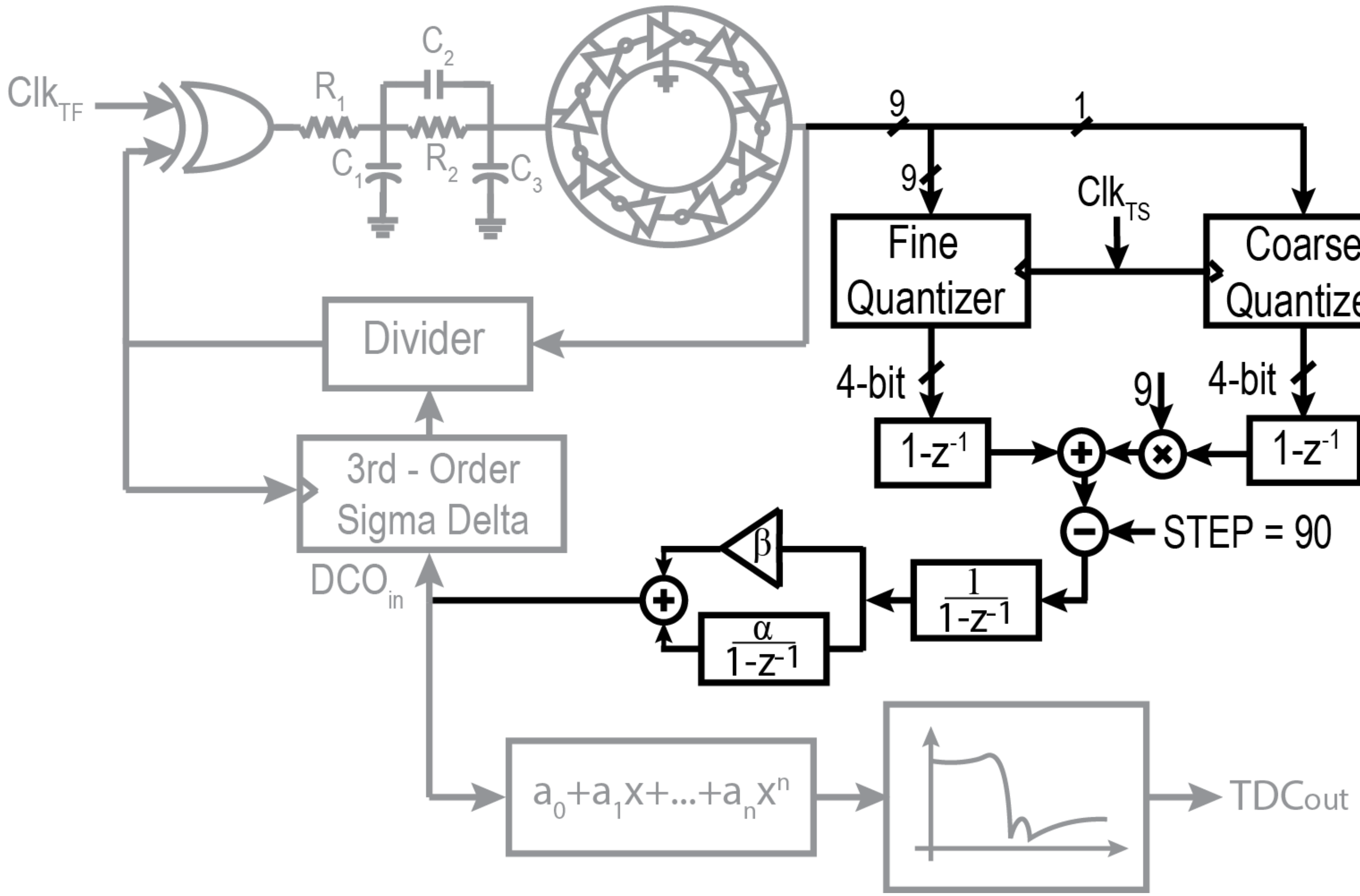

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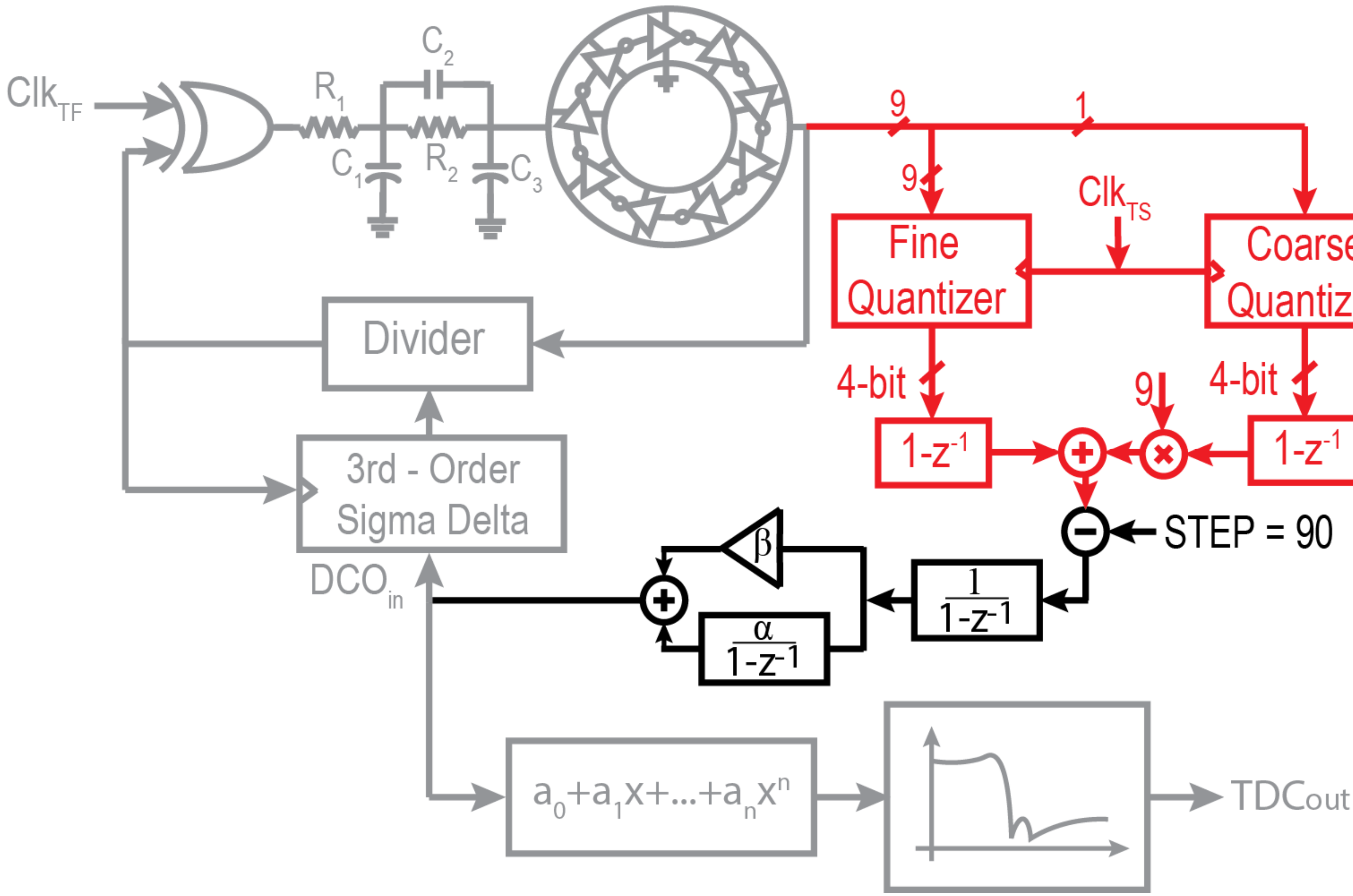
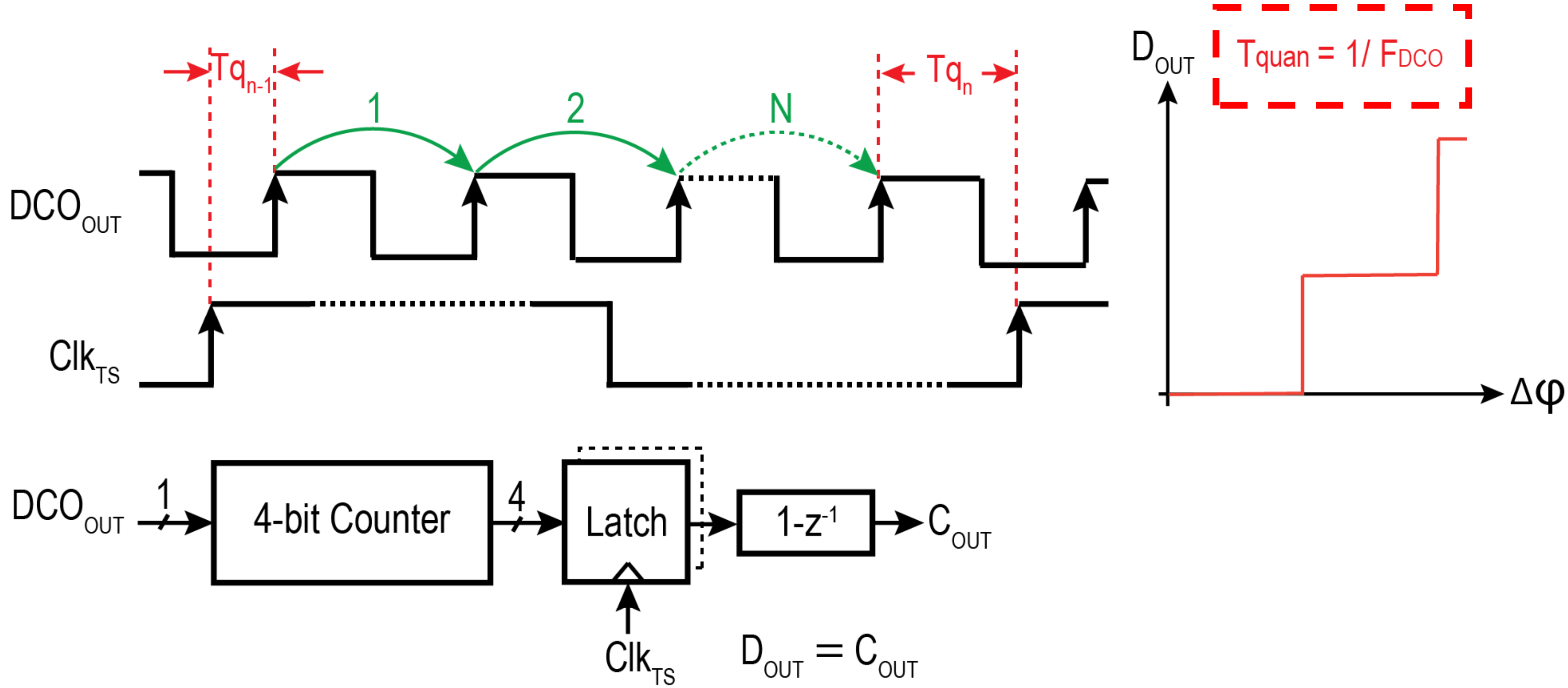
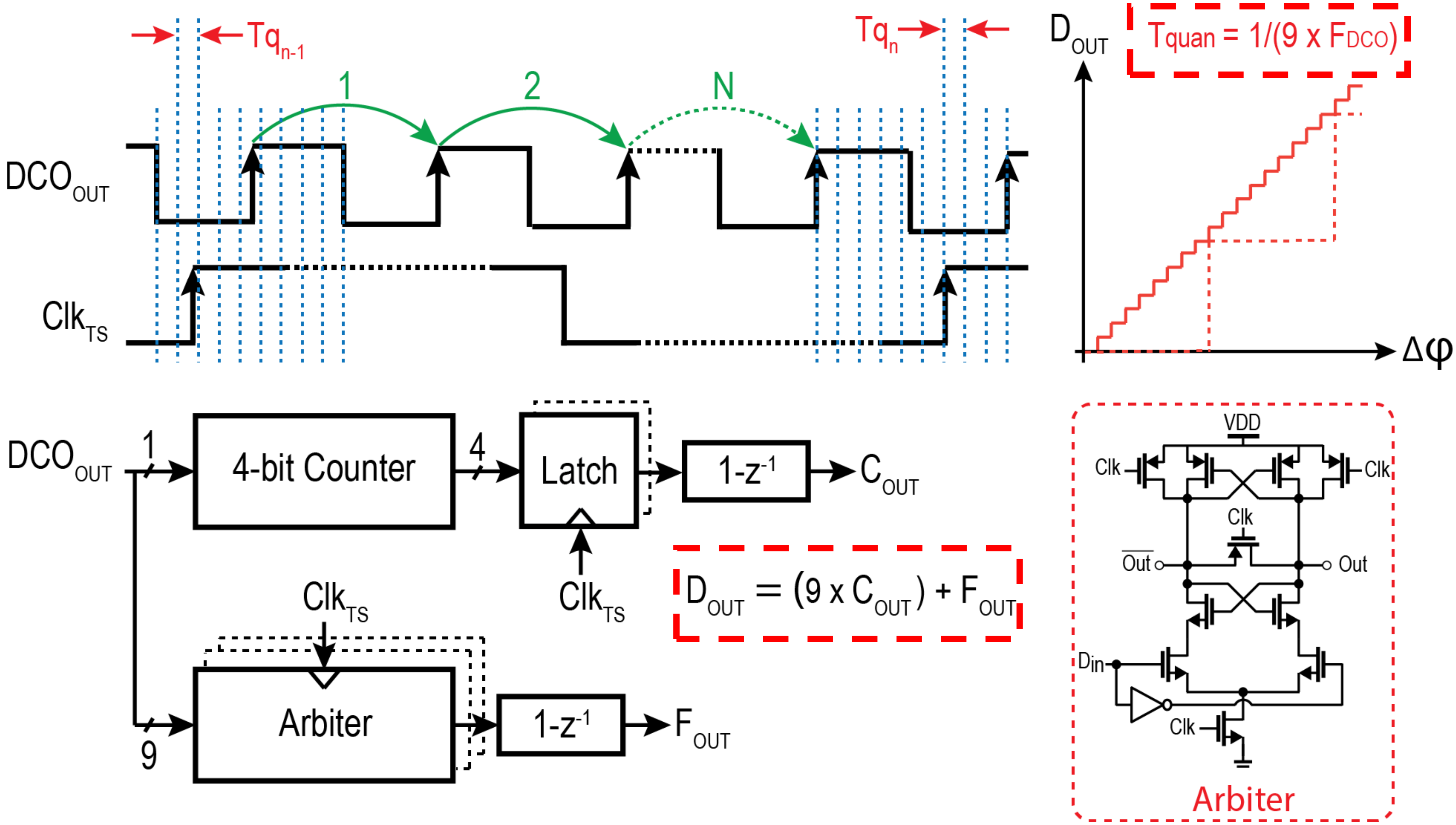


Digital PFD



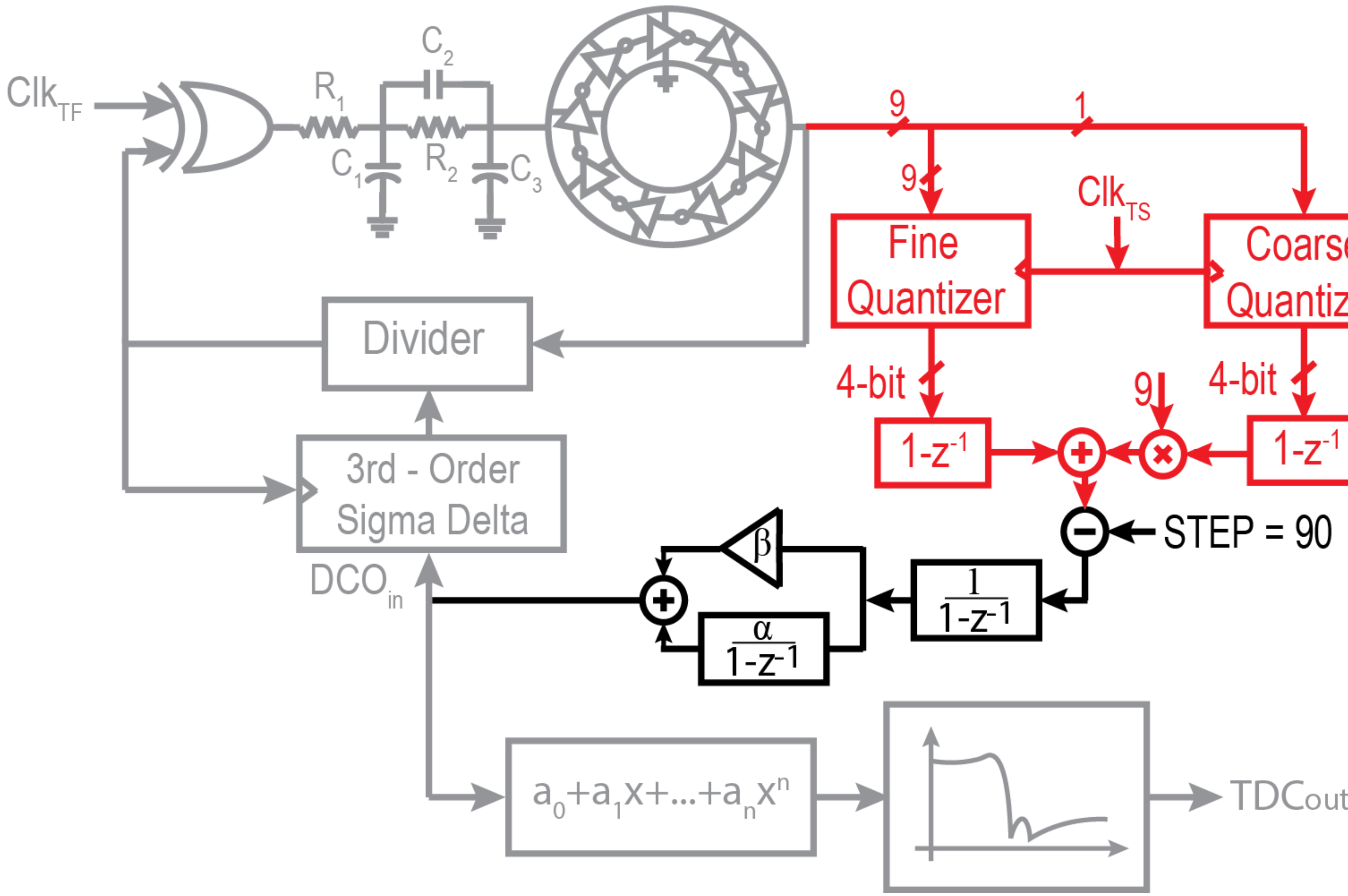
Tq$_{n-1}$
1
2
N
Tq$_n$
DCO$_{OUT}$
Clk$_{TS}$
D$_{OUT}$
Tquan = 1/ F$_{DCO}$
Δφ
DCO$_{OUT}$
1
4-bit Counter
4
Latch
1-z^{-1}
C$_{OUT}$
Clk$_{TS}$
D$_{OUT}$ = C$_{OUT}$

Digital PFD



$$D_{OUT} = (9 \times C_{OUT}) + F_{OUT}$$

More Details



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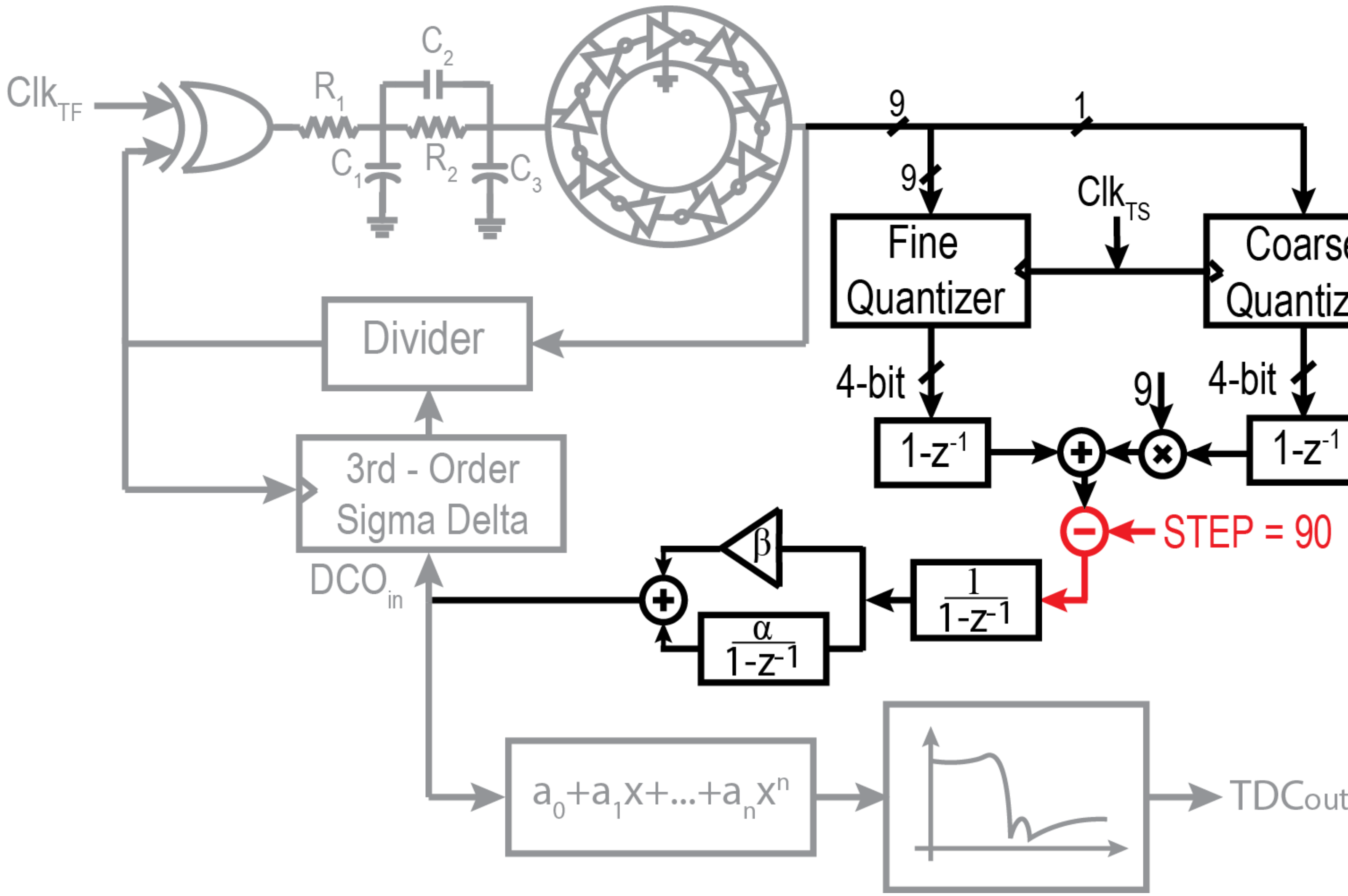

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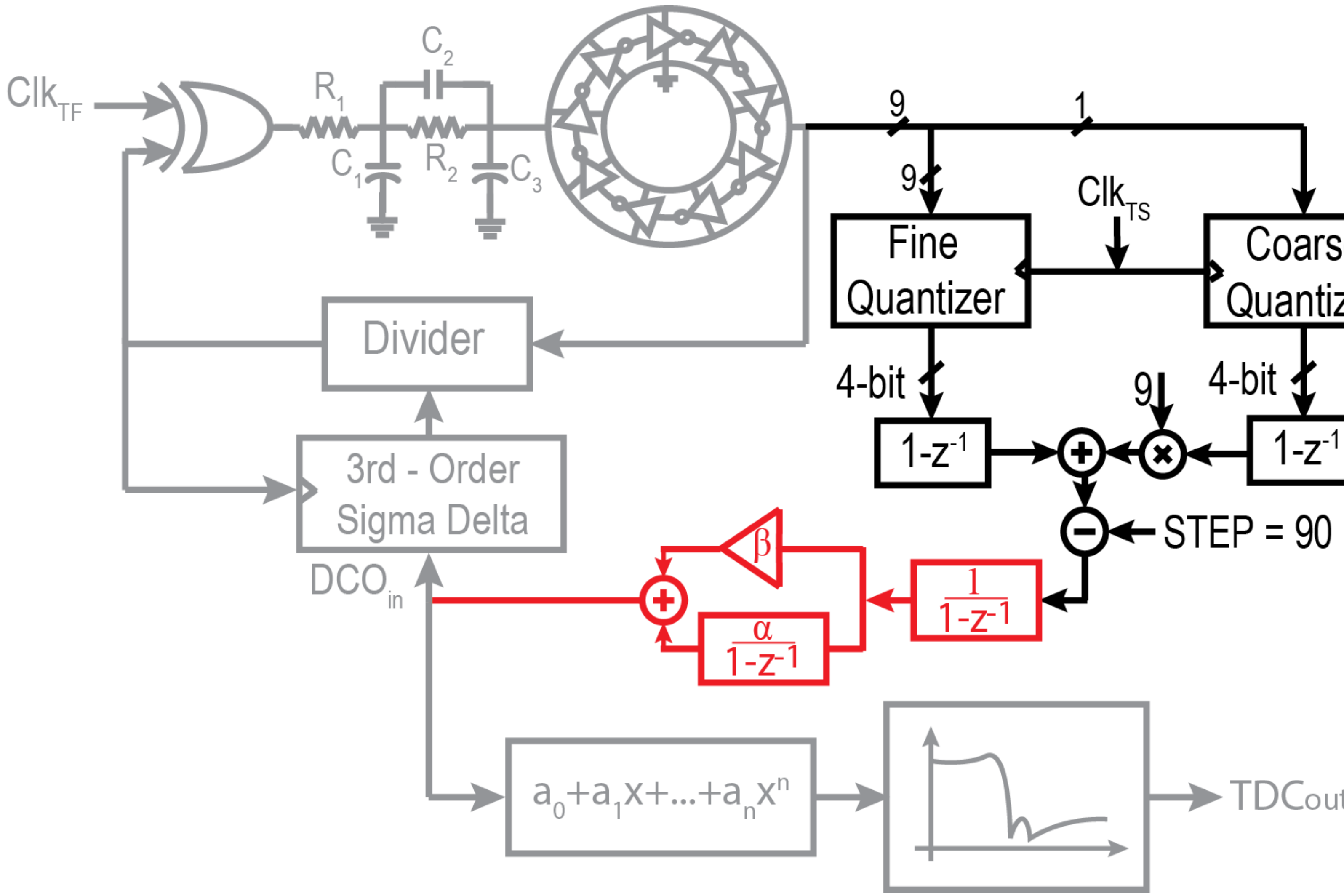

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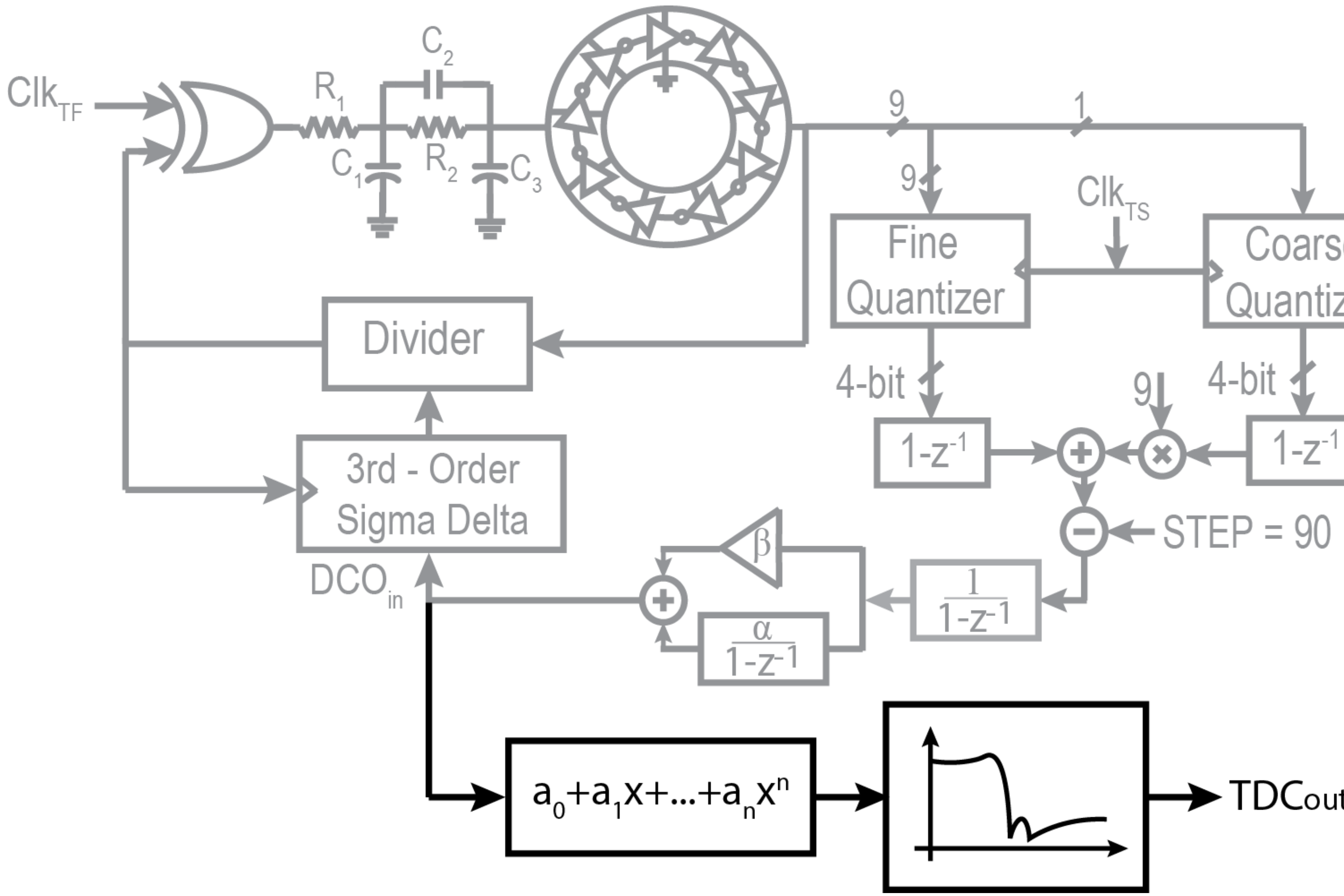
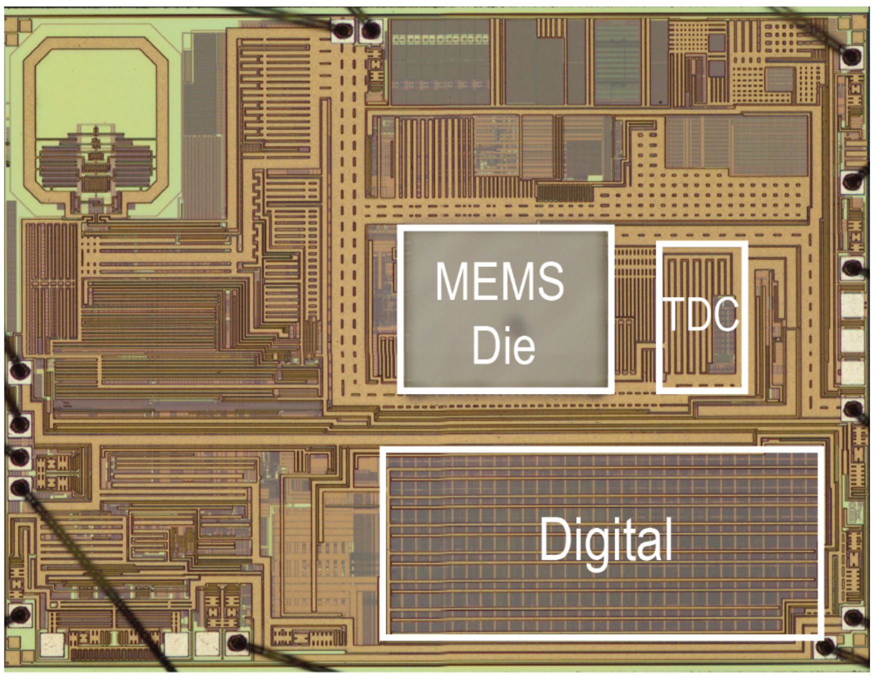
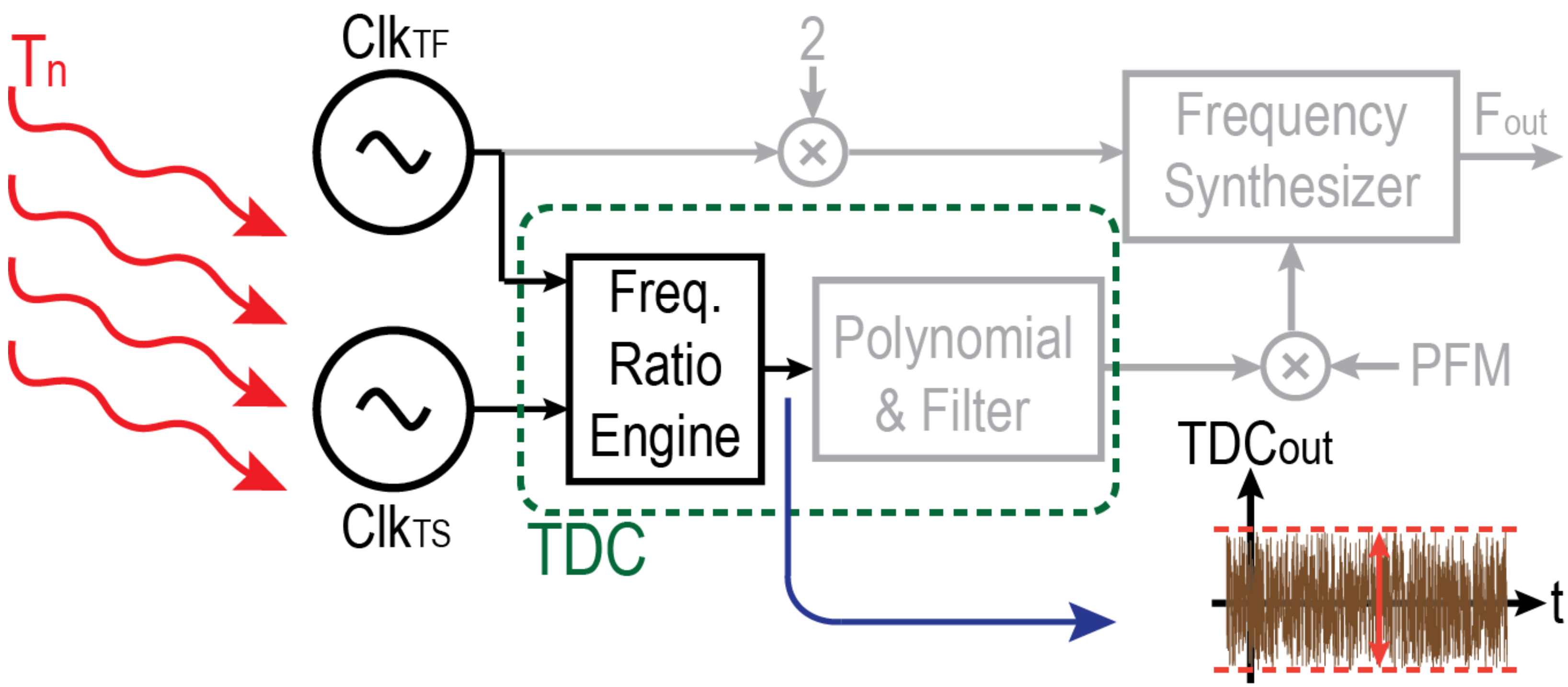


Chip Micrograph



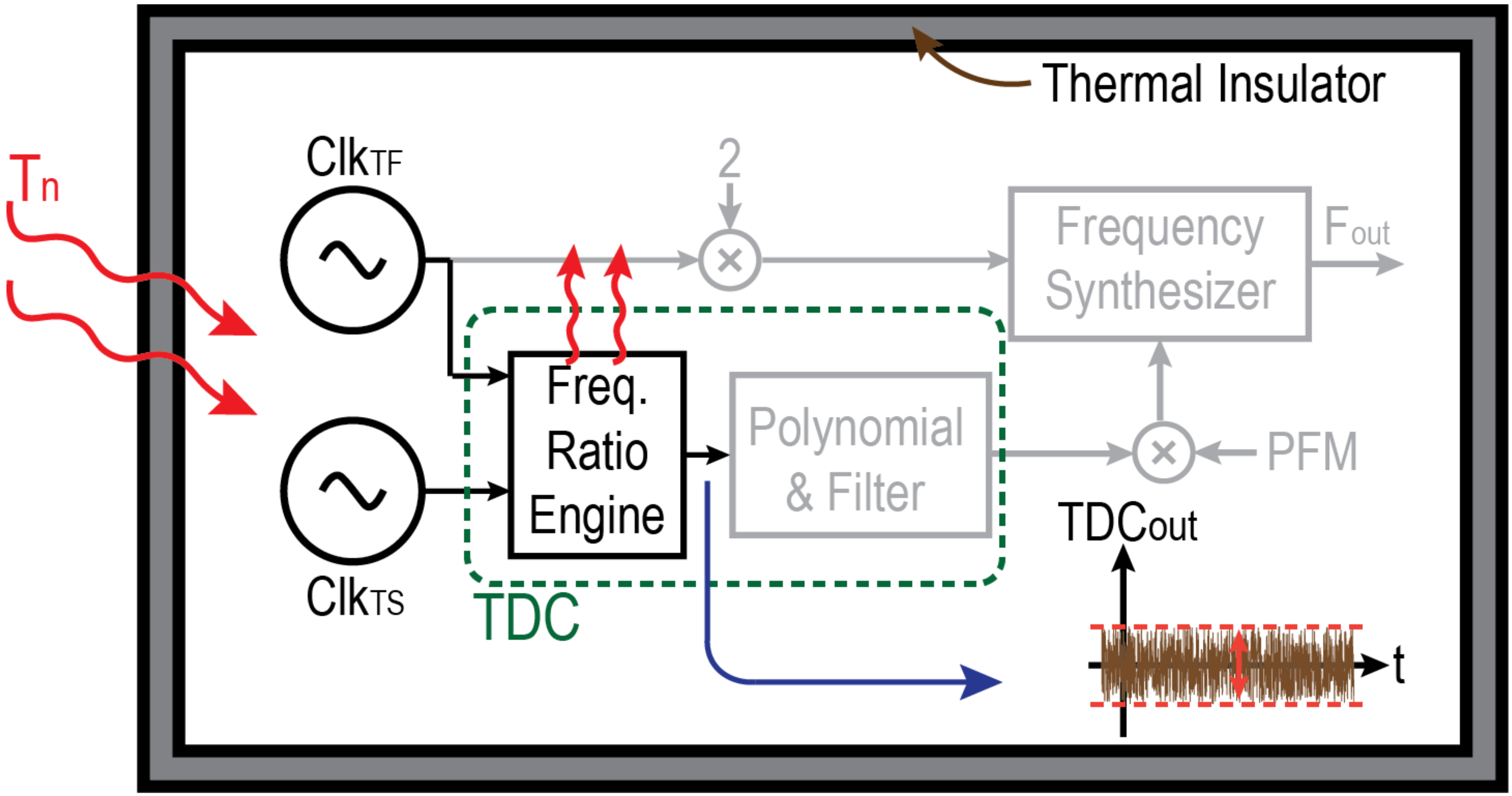
- 0.18μm CMOS
- $0.54mm^2$
  - Resonator included
- 12mA current for:
  - Sustaining circuits
  - Frequency ratio engine
  - Digital
- Supply voltage: 1.6V

Resolution Measurement Setup



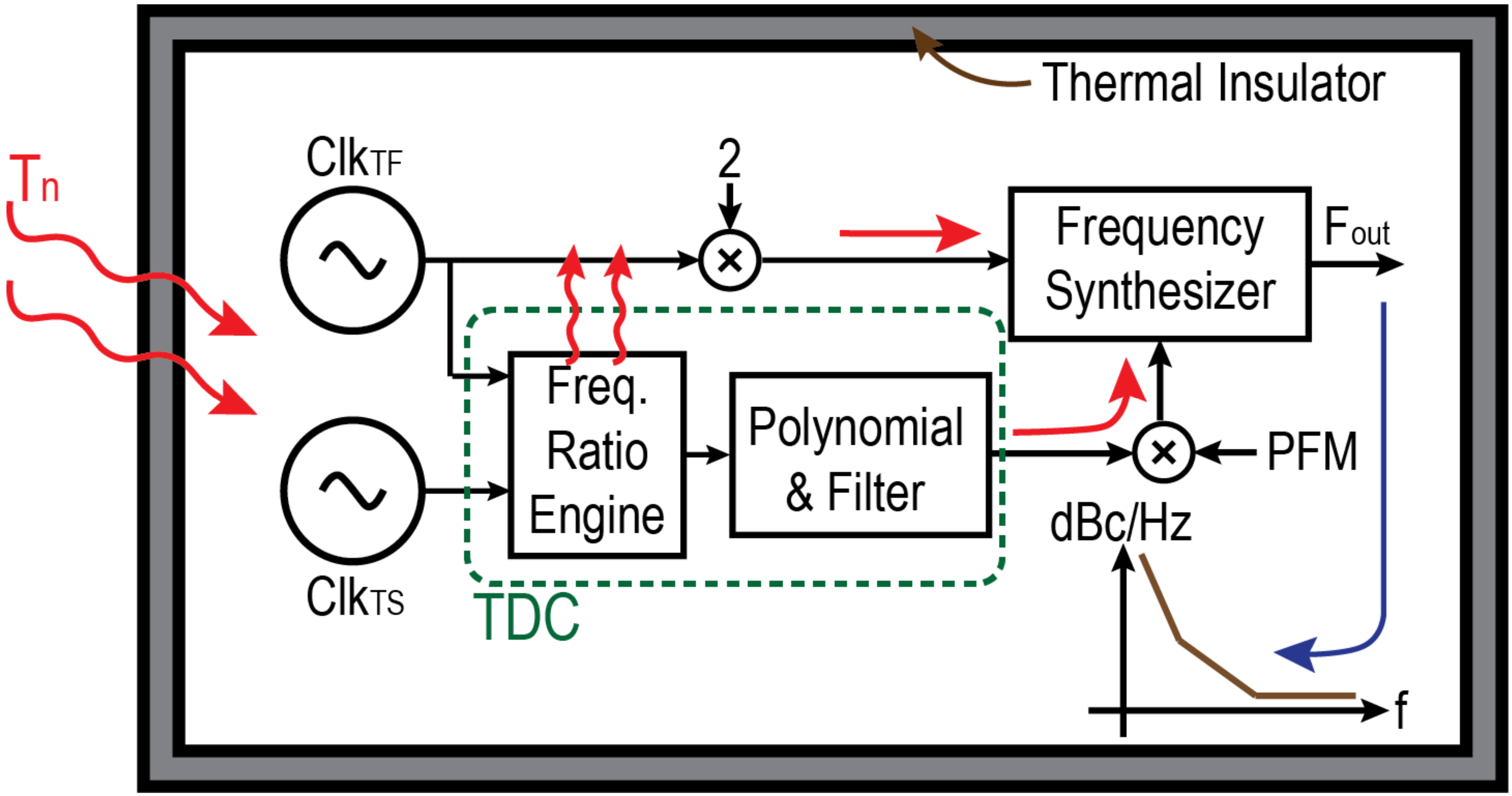
Thermal insulator is needed

Resolution Measurement Setup



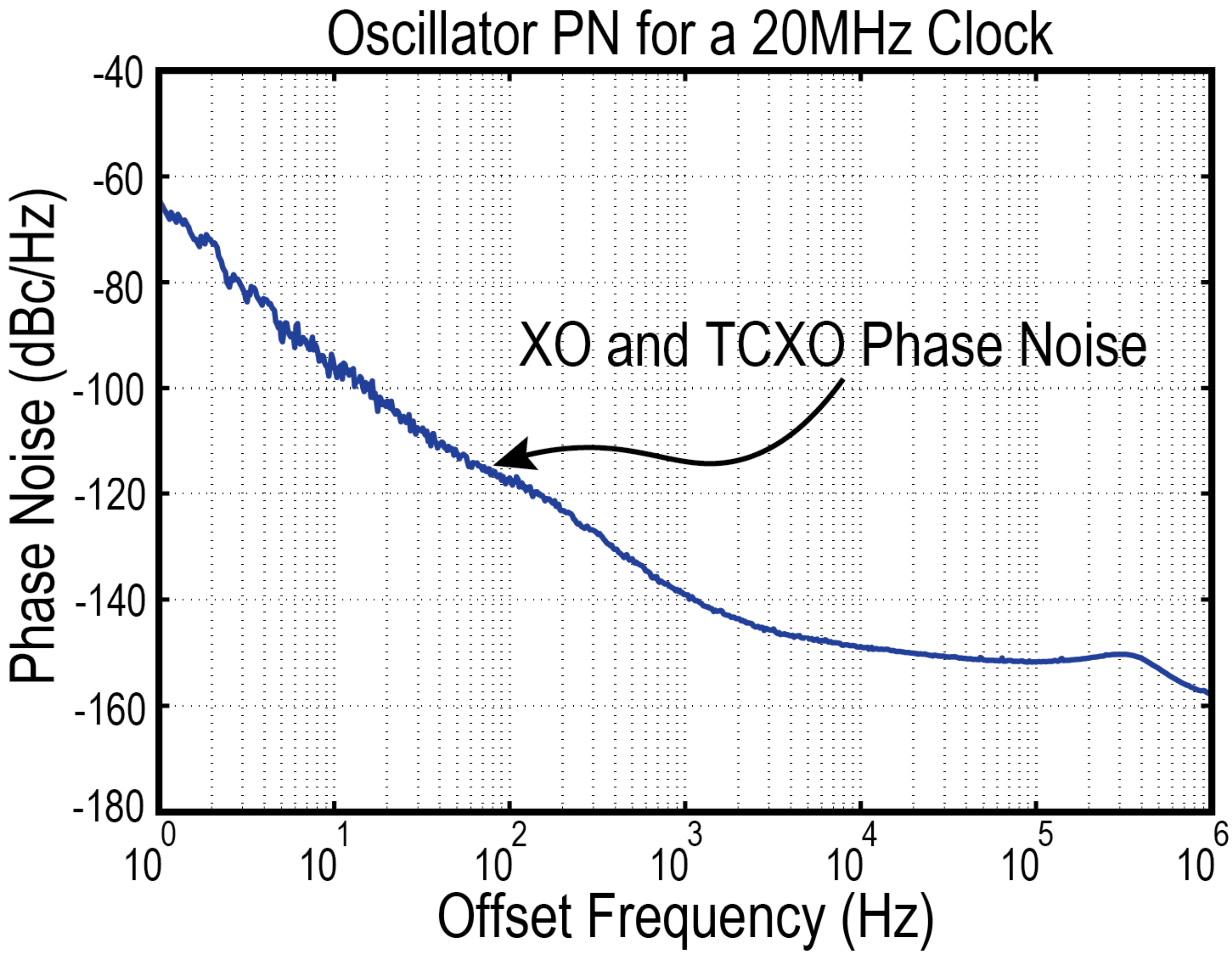
Environmental noise dominates the TDC resolution

Resolution Measurement Setup



Instead of TDC output, clock PN is measured

TDC Contribution on PN



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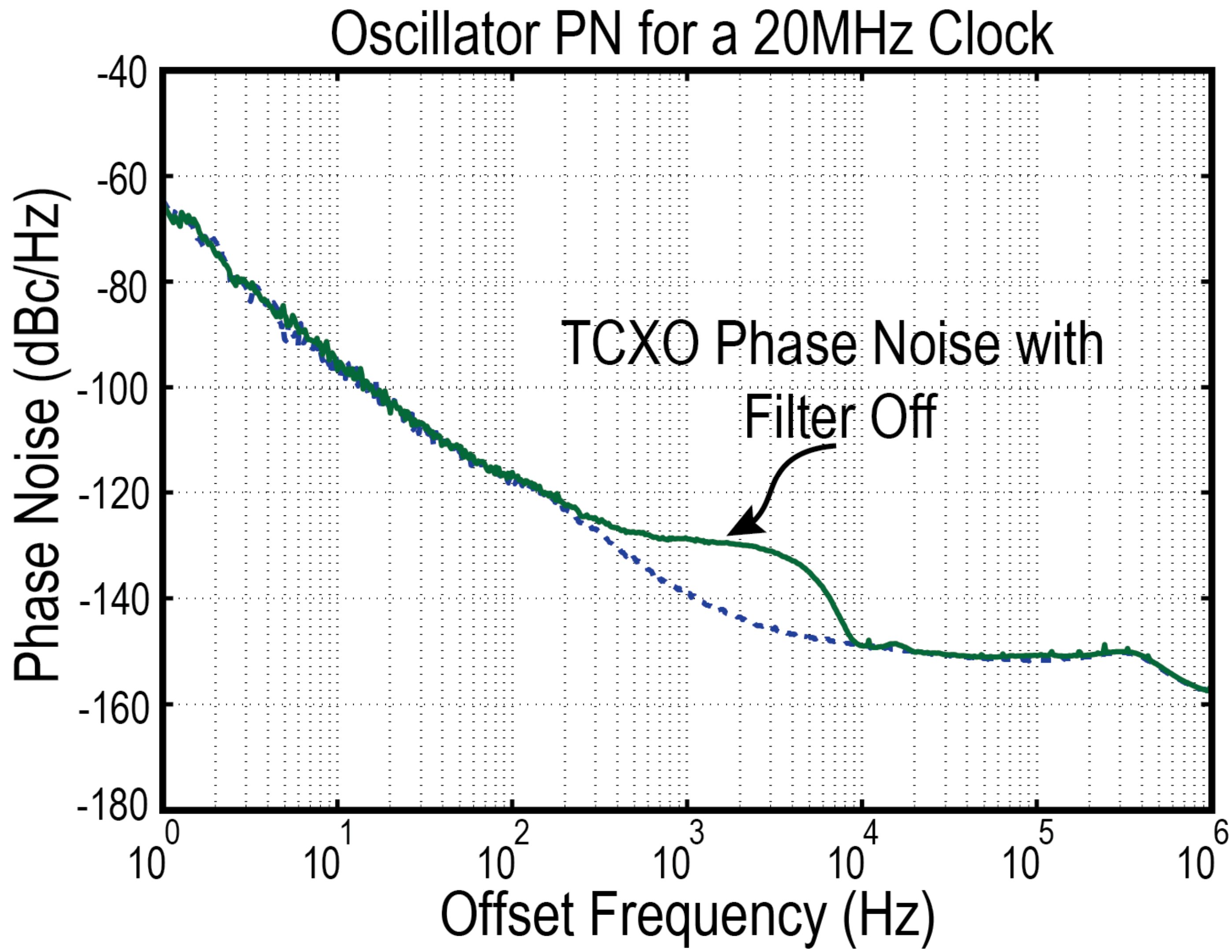
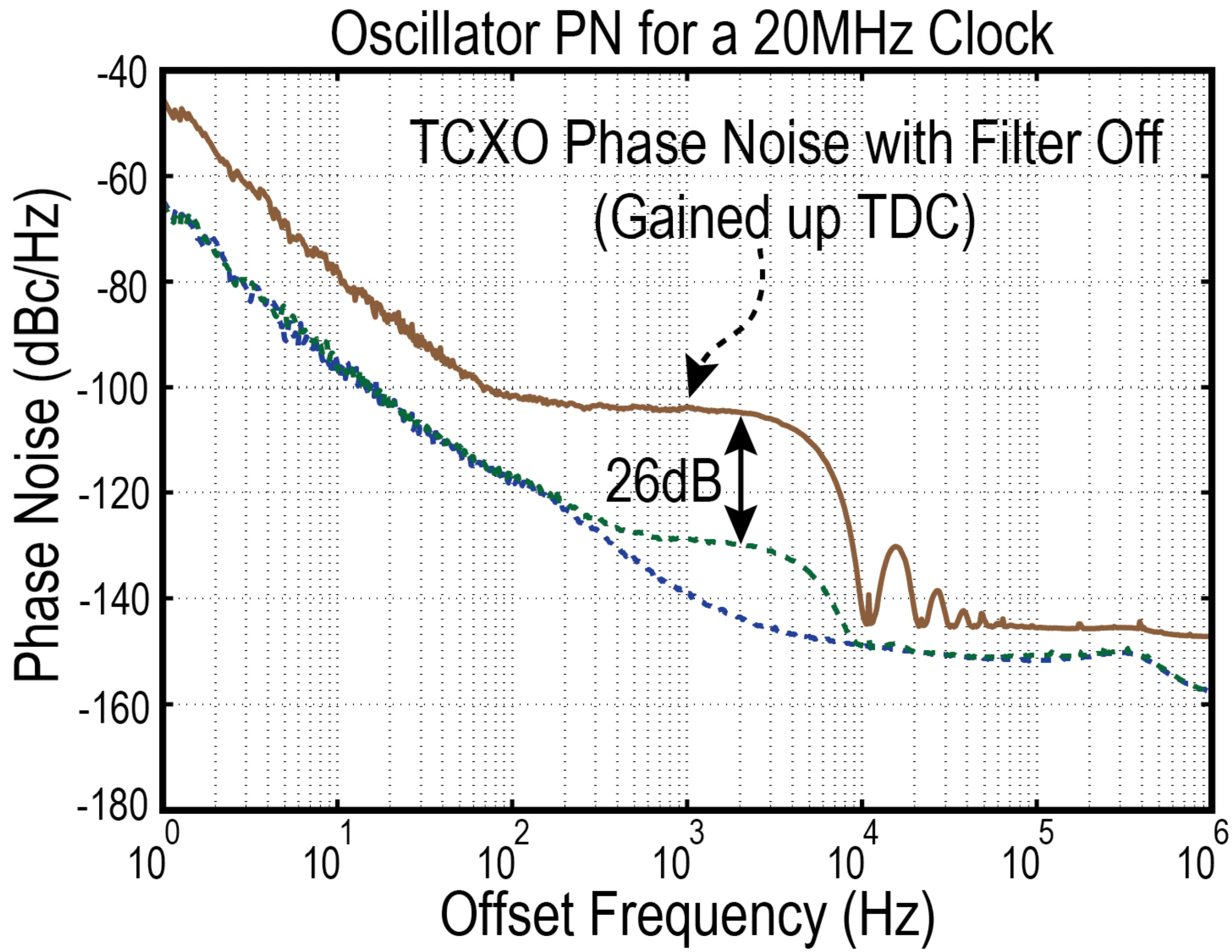
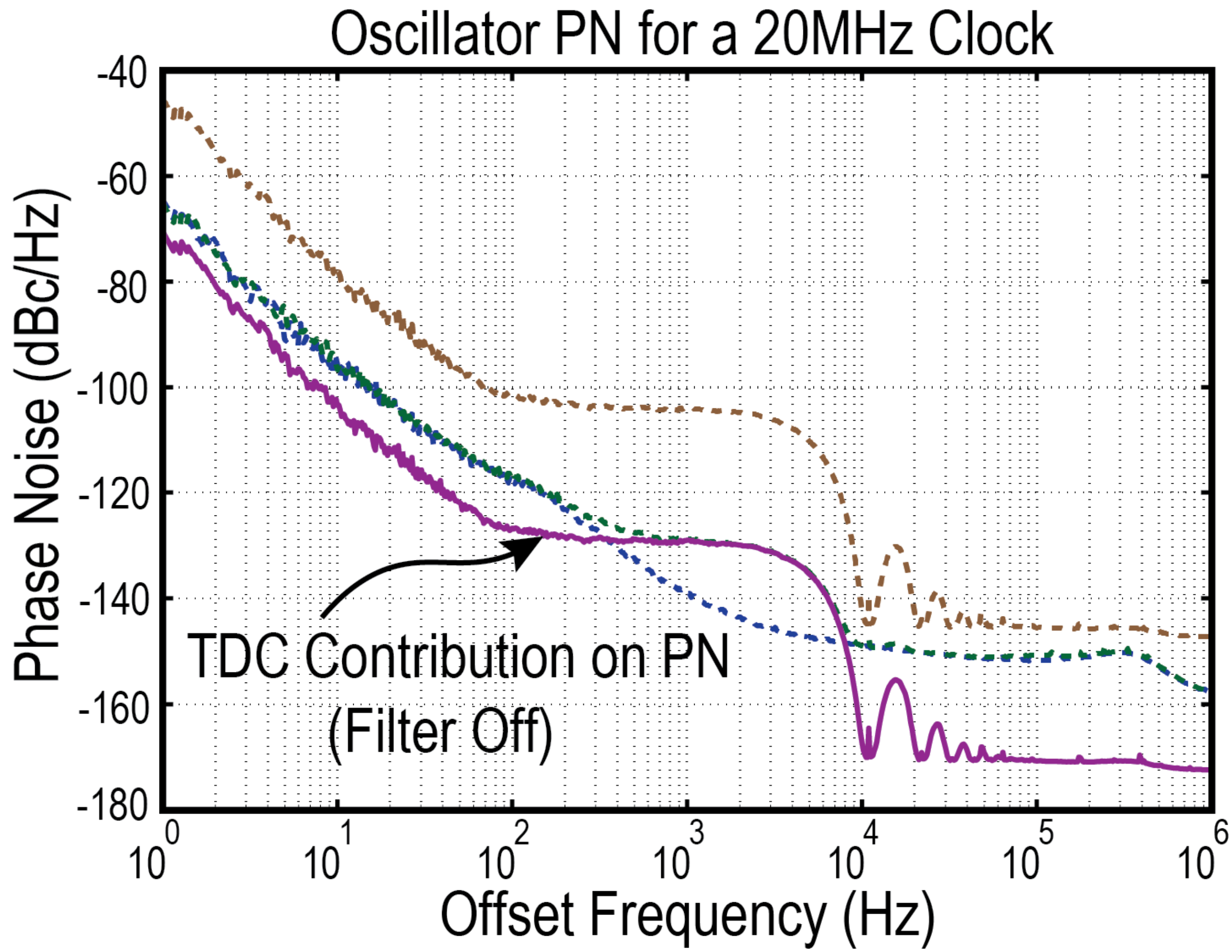


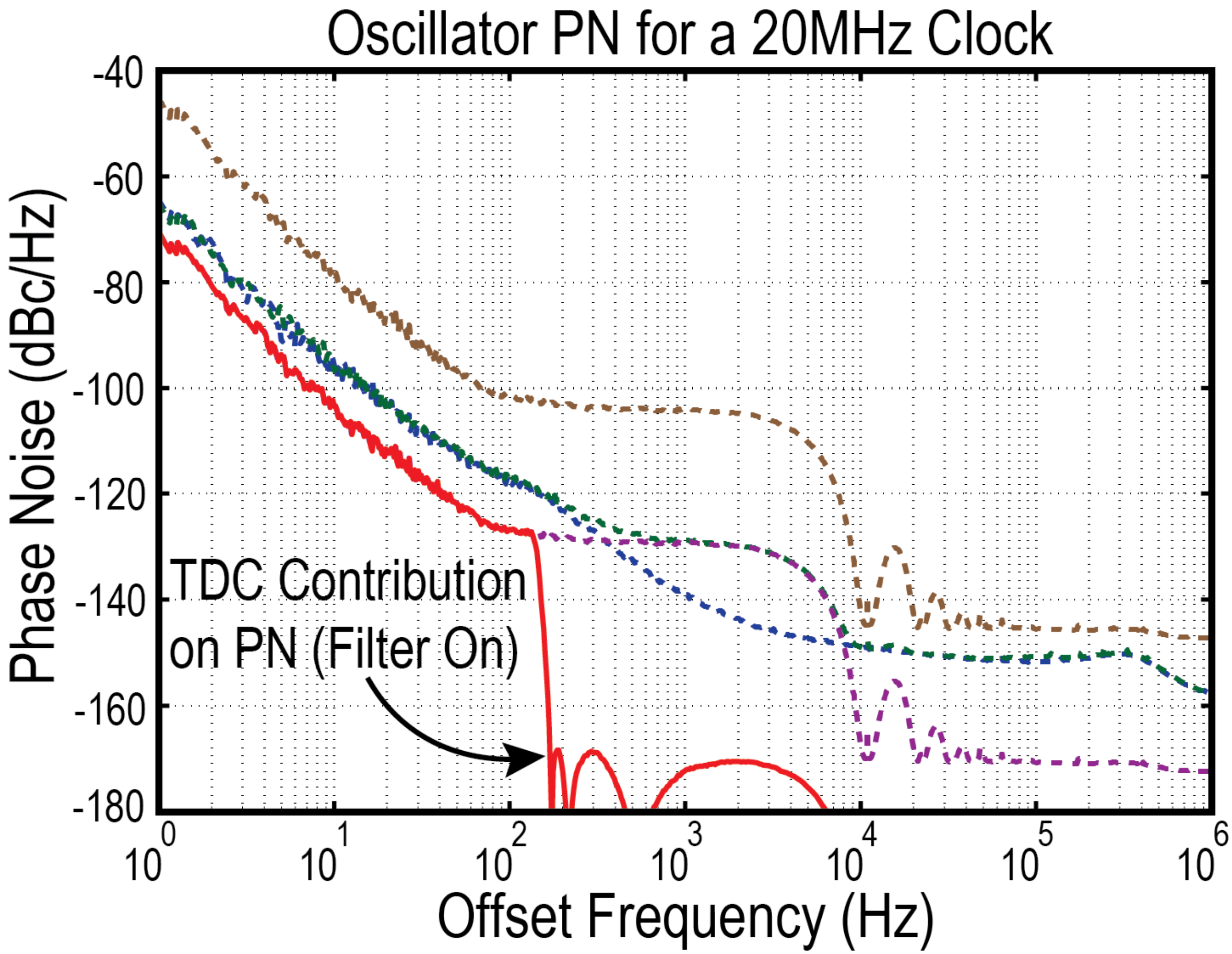
TDC Contribution on PN



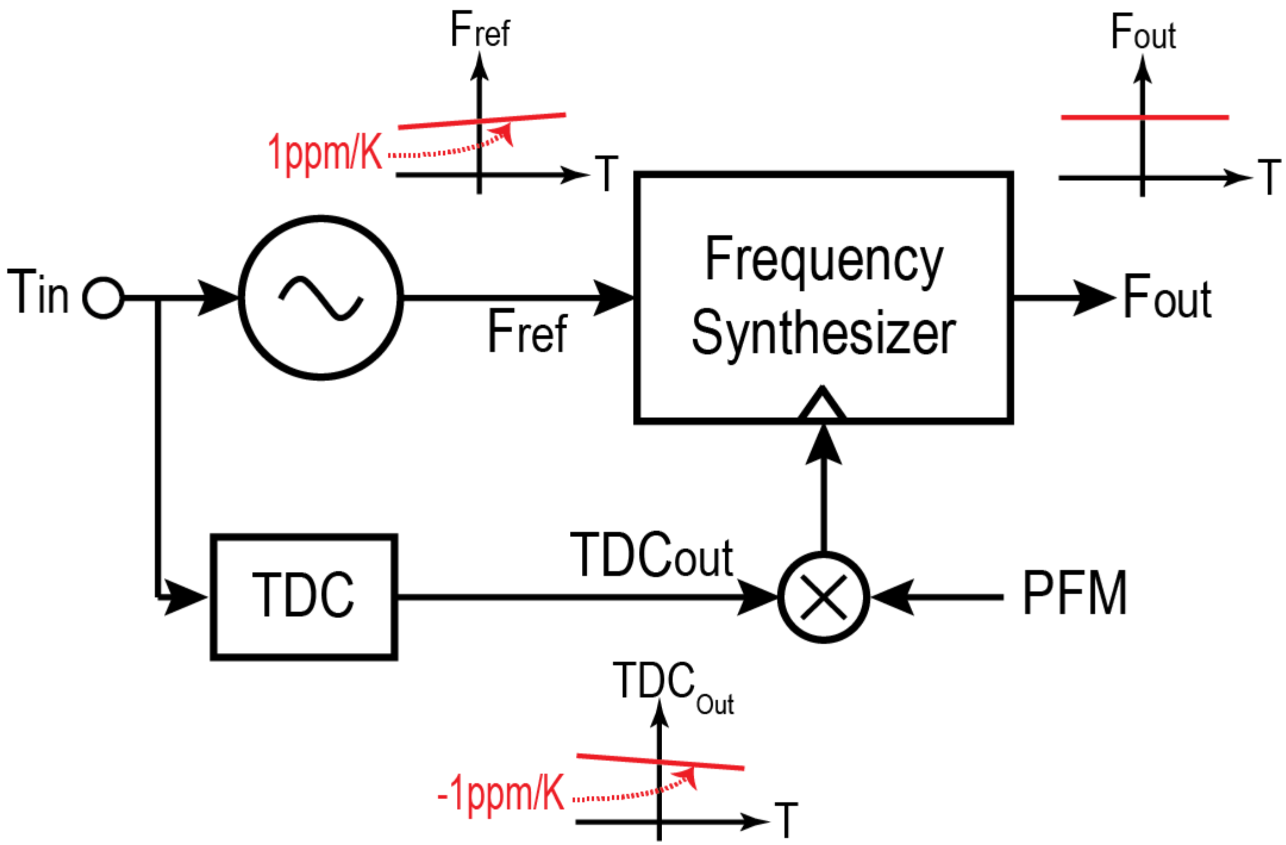
TDC Contribution on PN



TDC Contribution on PN



TCXO with Gained-up TDC



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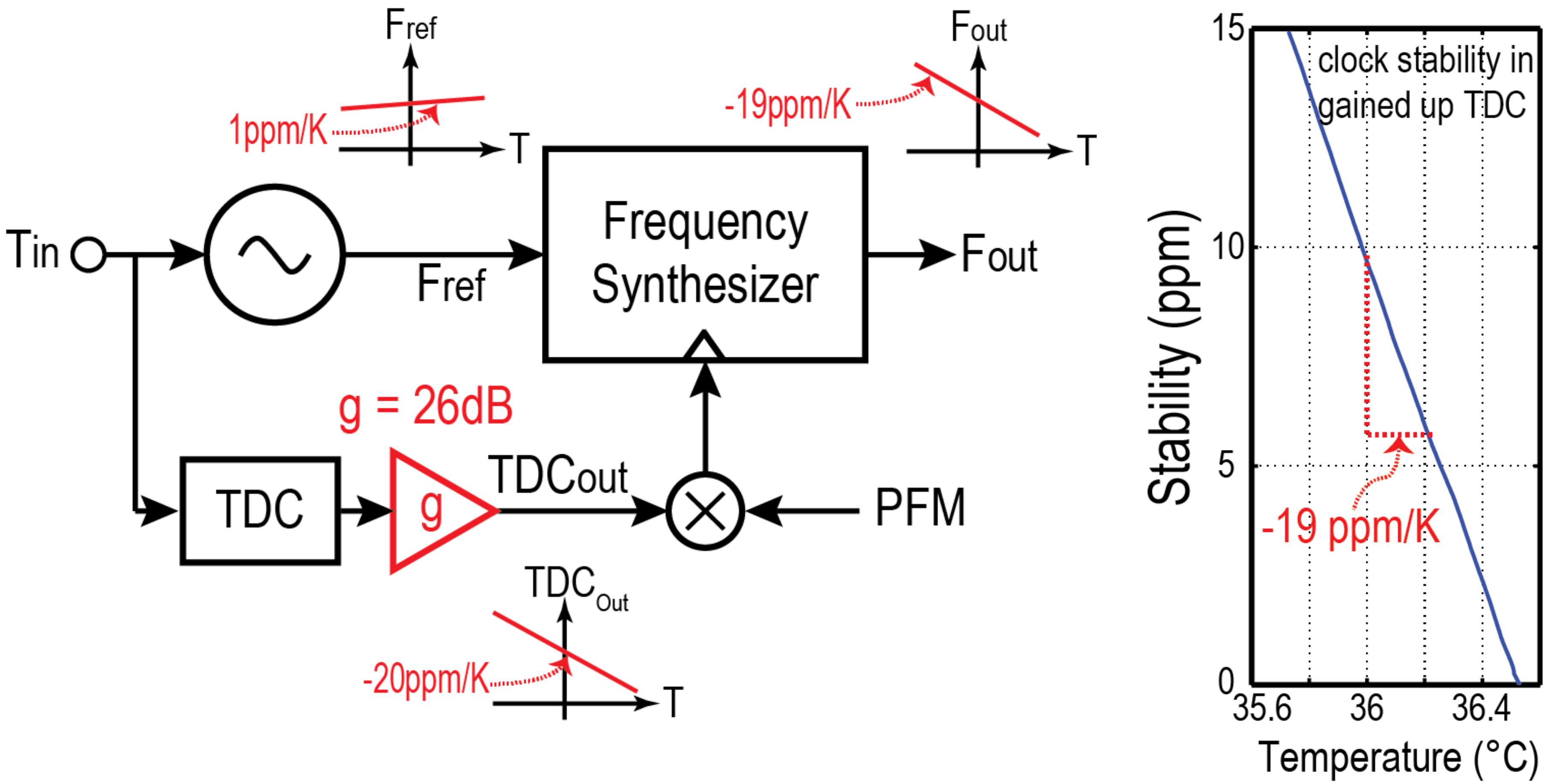
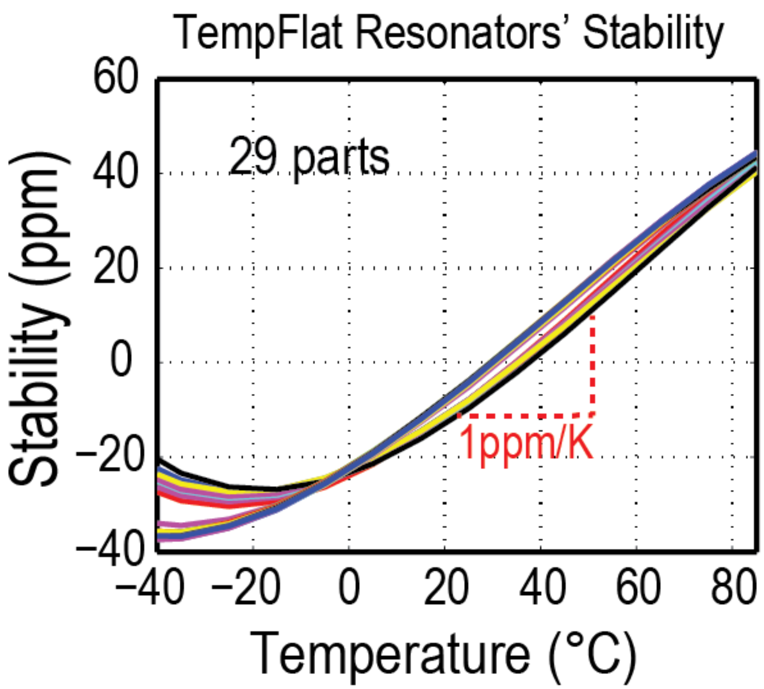
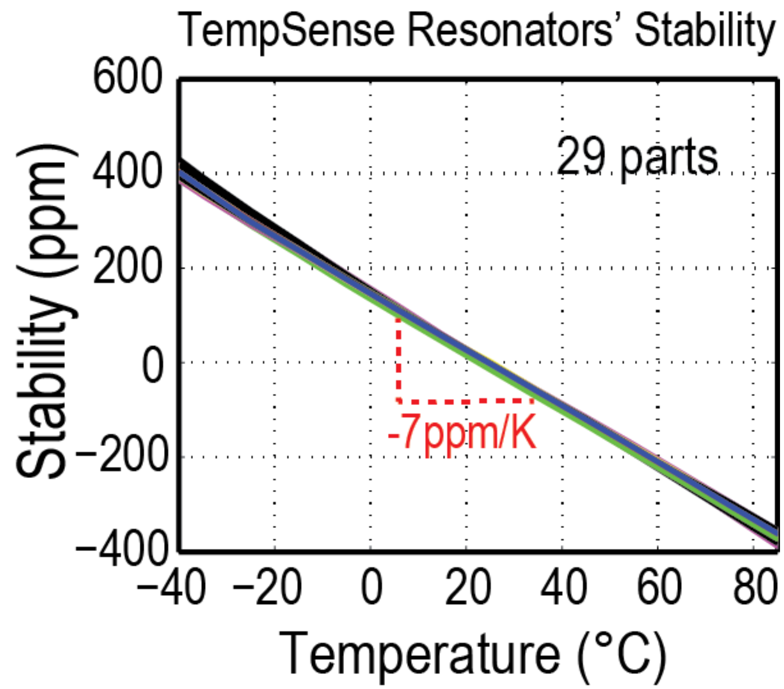


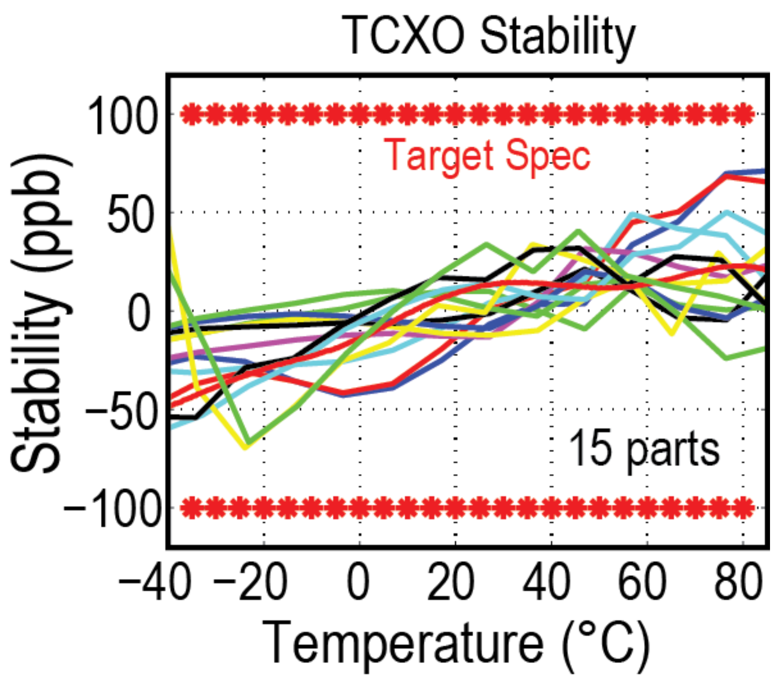
TDC has 40μK resolution over a BW of 130Hz

MEMS Resonators' Stability Measurements





Measured TCXO's Stability



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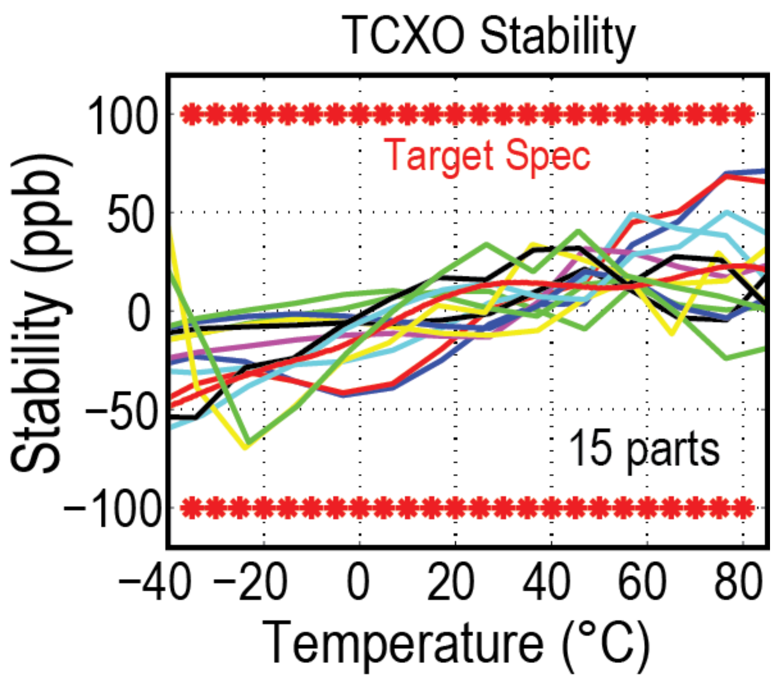
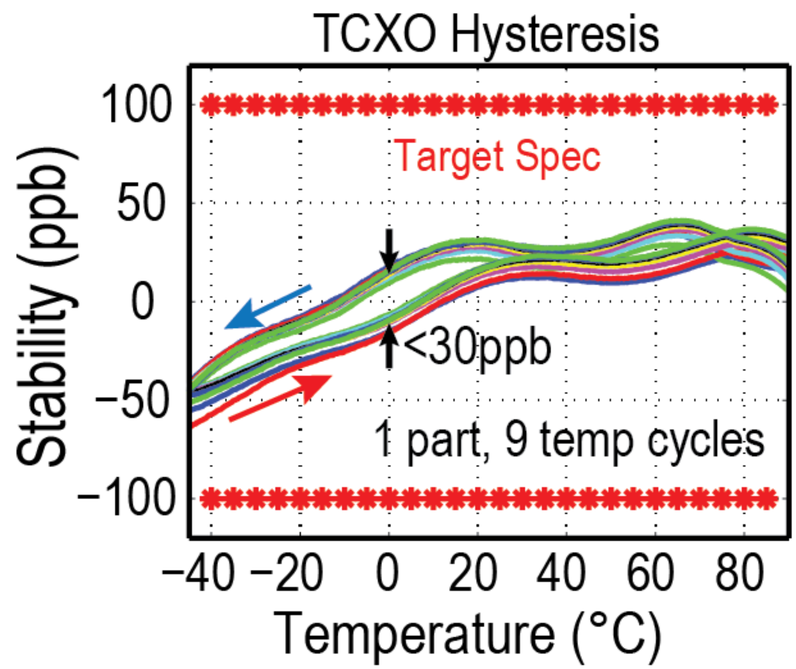
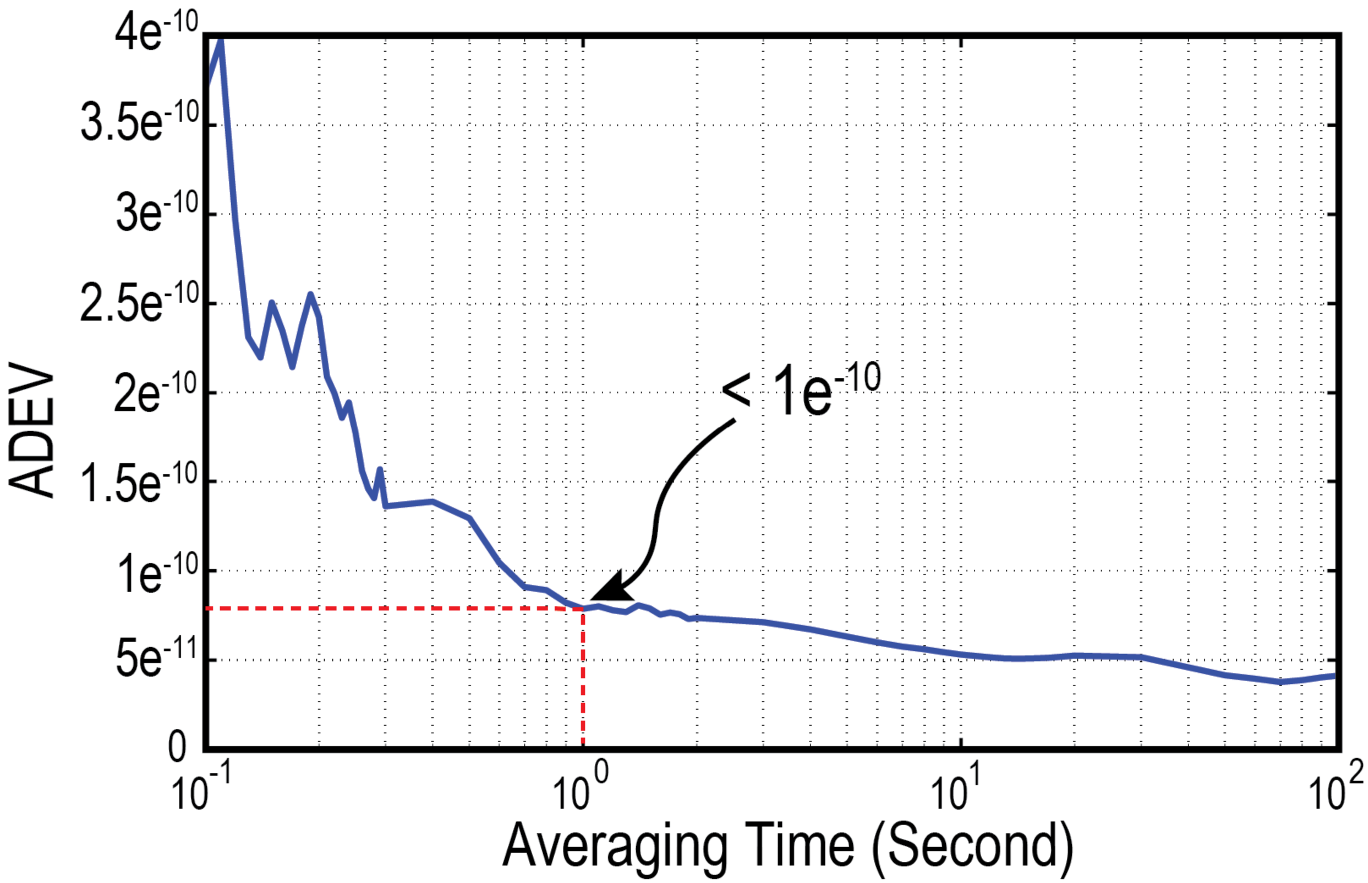




Allan Deviation Measurement

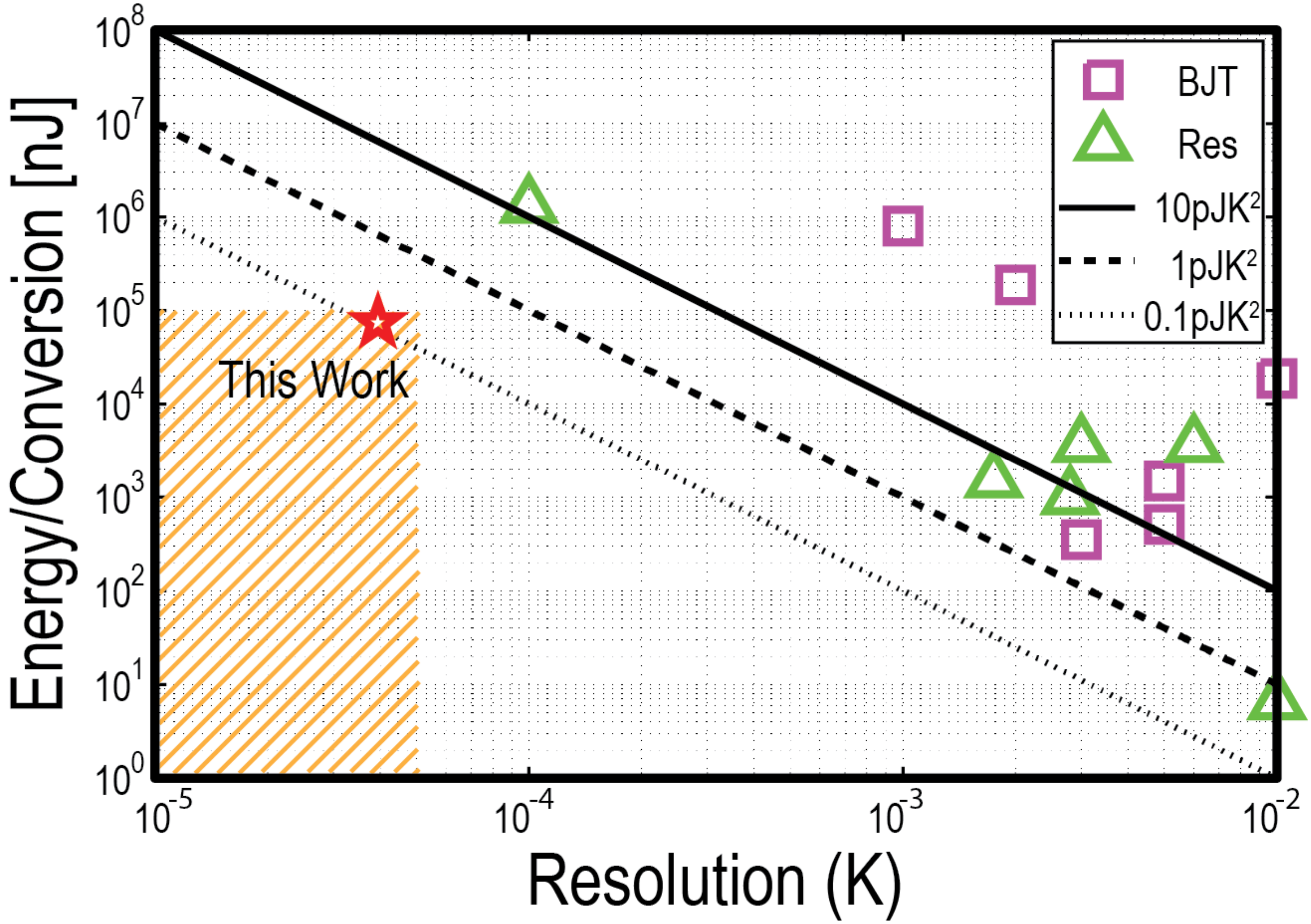


TCXO meets the ADEV target of $< 1e^{-10}$

Comparison Table

Parameter	This Work	C. H. Weng [JSSC'15]	P. Park [JSSC'15]	M. Perrott [ISSCC'12]	A. Heidary [ISSCC'14]
Sensor Type	Dual-MEMS Resonator	Resistor	Resistor	Resistor	BJT
CMOS Technology	0.18µm	0.18µm	0.18µm	0.18µm	0.7µm
Area	0.54 mm^2	0.43 mm^2	0.09 mm^2	0.18 mm^2	0.8 mm^2
Power Consumption	19 mW	64.5 µW	31 µW	13 mW	159 µW
Temperature Range	-40 to 85°C	-45 to 125°C	-40 to 85°C	-40 to 85°C	-45 to 130°C
Conversion Time	3.85ms	0.1ms	32ms	100ms	2.2ms
Resolution	0.04mK	10mK	2.8mK	0.1mK	3mK
FOM	0.12pJK^2	0.65pJK^2	8pJK^2	13pJK^2	3.2pJK^2

Energy/Conversion vs. Resolution*



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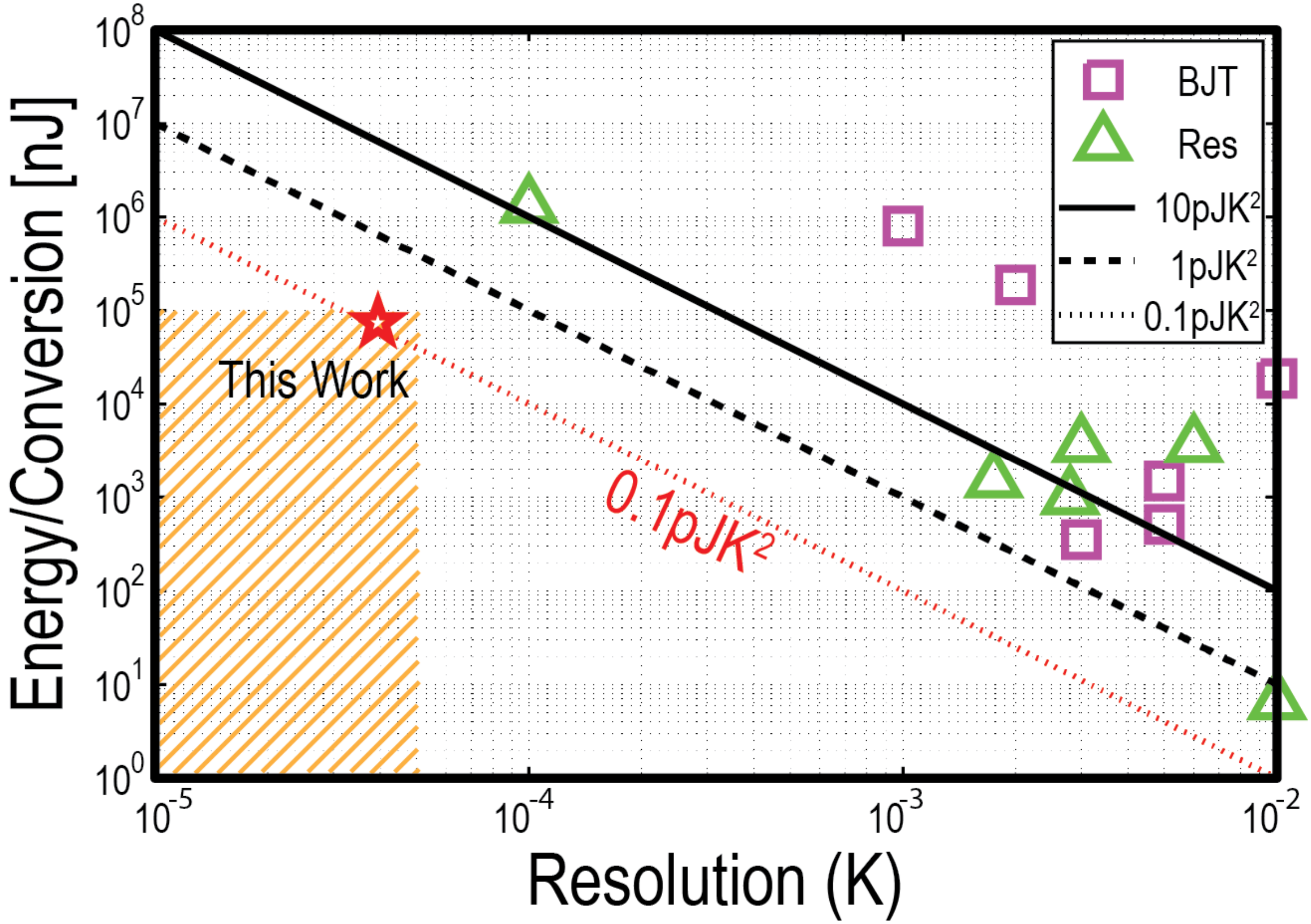
Energy/Conversion vs. Resolution*



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  - Resolution of 40μK → 2.5x improvement
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- Dual-MEMS-Resonator TDC:
  - Resolution of 40µK → 2.5x improvement
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- MEMS-Based Oscillator for telecom applications:
  - Allan Deviation of < $1e^{-10}$ in 1s averaging time
  - Frequency stability of < ±0.1ppm
  - Temperature range of -40°C to 85°C

Acknowledgement

- Prof. Kofi Makinwa for his support, review, and comments!

- Nazariy Tshchynskyy, Anton Prygrodskyi and Trushal Chokshi from SiTime for their dedicated support during the measurements