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A Center Frequency Calibration Technique for Ring VCO Exploiting Delay^{-1} Detection

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Contents

Motivation——VCO-based ADC

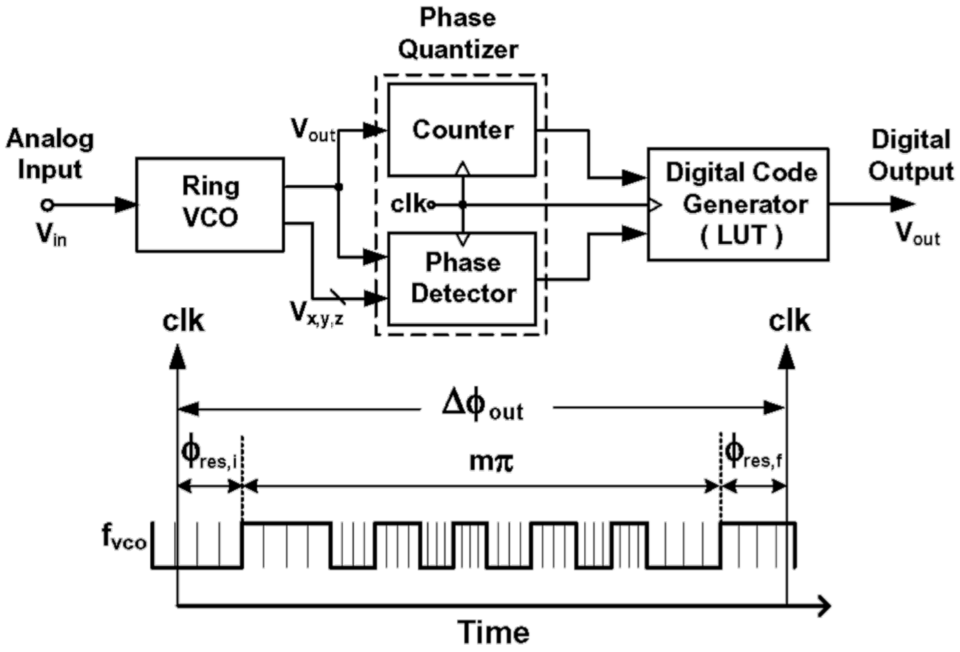
- **Benefits from a VCO-based quantization process**
  - Higher resolution
  - Immune to DAC mismatch error

- **Performance degradation due to a PVT-sensitive ring VCO**
  - Tuning gain variation: conversion gain variation
  - **Center frequency variation: offset → loss of DR & saturation problem**

- **Approaches to solve the problem caused by center frequency variation**
  - Using counters
  - Calibration based on the replica signal paths or replica-VCOs

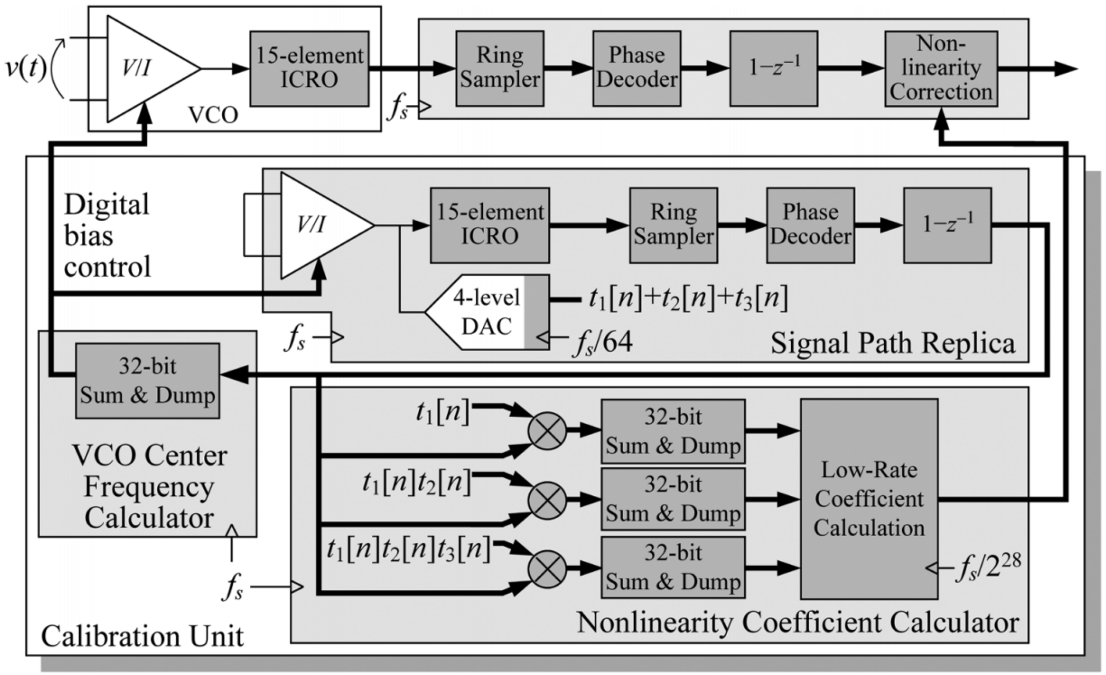
Review of previous arts

- **Using counters**



[J. Kim, ISCAS'2006]

- **Calibration based on replicas**



[G. Taylor, JSSC'2010]

- Immune to center frequency variation ☺
- High-speed sampling ☹

- Center frequency calibration ☺
- Hardware consumption ☹

Proposed calibration technique

- **Oscillation frequency of an ideal VCO:** $f_{\text{out, ideal}} = f_{\text{c, ideal}} + k_{\text{VCO}} \cdot \left(V_{\text{inp}} - V_{\text{inm}}\right)$
- **Oscillation frequency of an actual VCO:** $f_{\text{out}} = \left(f_{\text{c, ideal}} + \Delta f_{\text{c}}\right) + k_{\text{VCO}} \cdot \left(V_{\text{inp}} - V_{\text{inm}}\right)$

deviation of the center frequency

- **Driving the VCO with a reverse signal:** $f_{\text{out, reverse}} = \left(f_{\text{c, ideal}} + \Delta f_{\text{c}}\right) + k_{\text{VCO}} \cdot \left(V_{\text{inm}} - V_{\text{inp}}\right)$
- **Calculating the deviation of the center frequency by:**

$$\Delta f_{\text{c}} = \frac{f_{\text{out}} + f_{\text{out, reverse}}}{2} - f_{\text{c, ideal}}$$

Detection using f_{out}

- **Utilizing the relation between f and τ:**

$$\Delta f_{\text{c}} = \frac{1}{2} \cdot \left(\frac{1}{2N \cdot \tau_{\text{d}}} + \frac{1}{2N \cdot \tau_{\text{d, reverse}}} \right) - f_{\text{c, ideal}}$$

Detection using τ_{d}

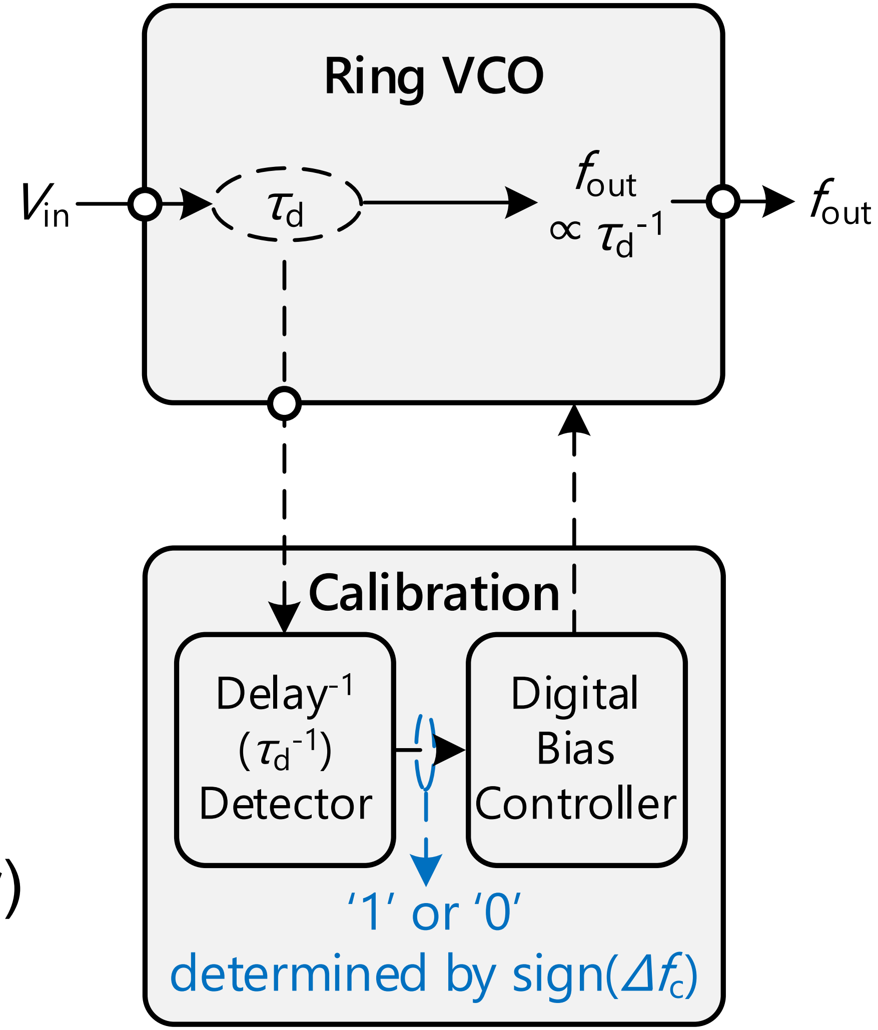
Either τ_{d} or f_{out} can be used for calibration!

Proposed calibration technique

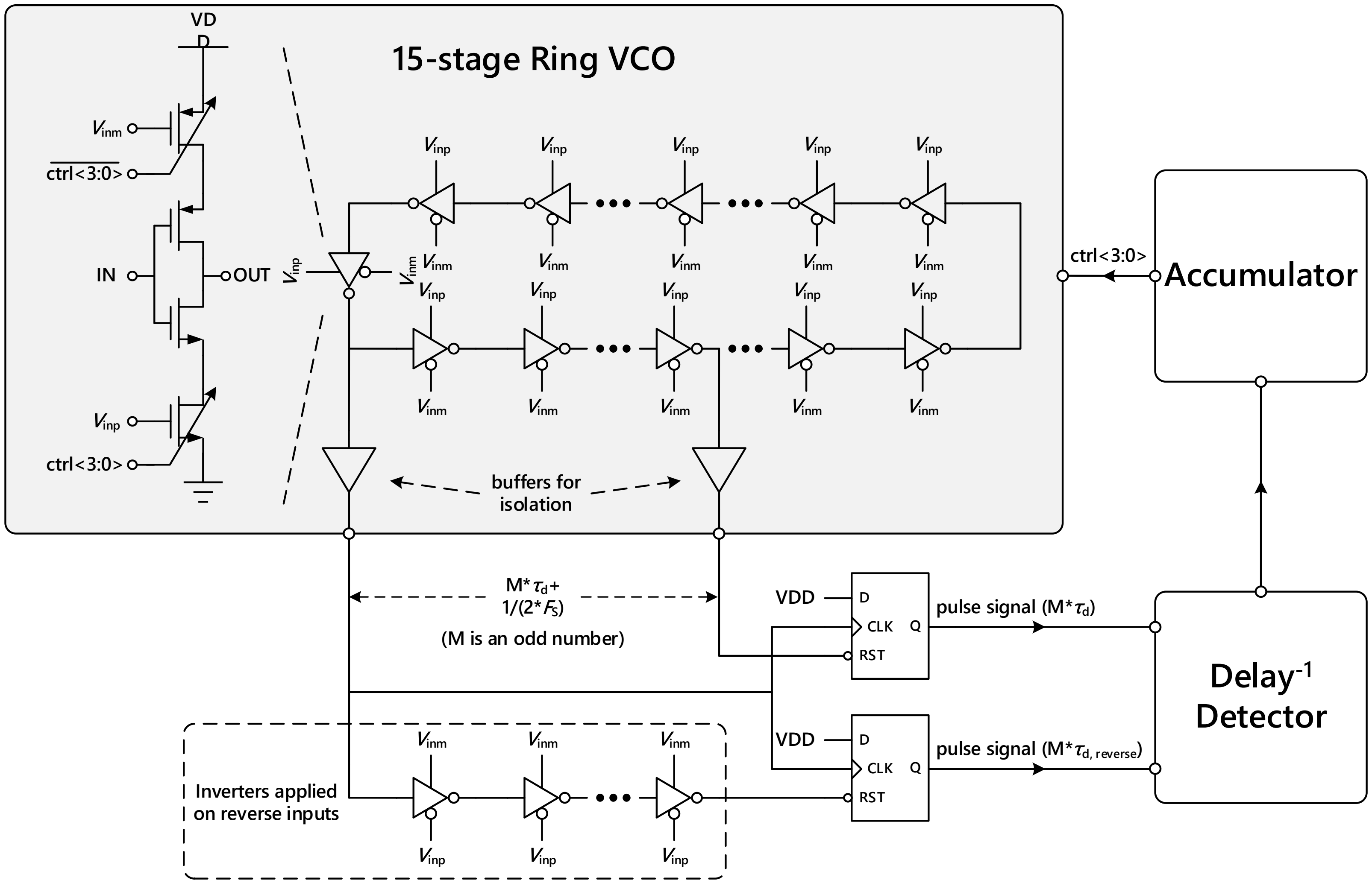
- **Two kinds of information in ring VCOs**
  - τ_d: generated by several delay cells
  - f_{out}: generated by a complete VCO

- **Calibration using τ_d**
  - **Effective**
    (well-defined relation between τ_d and f_{out})
  - **Hardware-efficient** (no replica-VCOs)

- **Two-step calibration**
  - Detection of Δf_c (achieved by delay^{-1} detector)
  - Correction (achieved by digital bias)



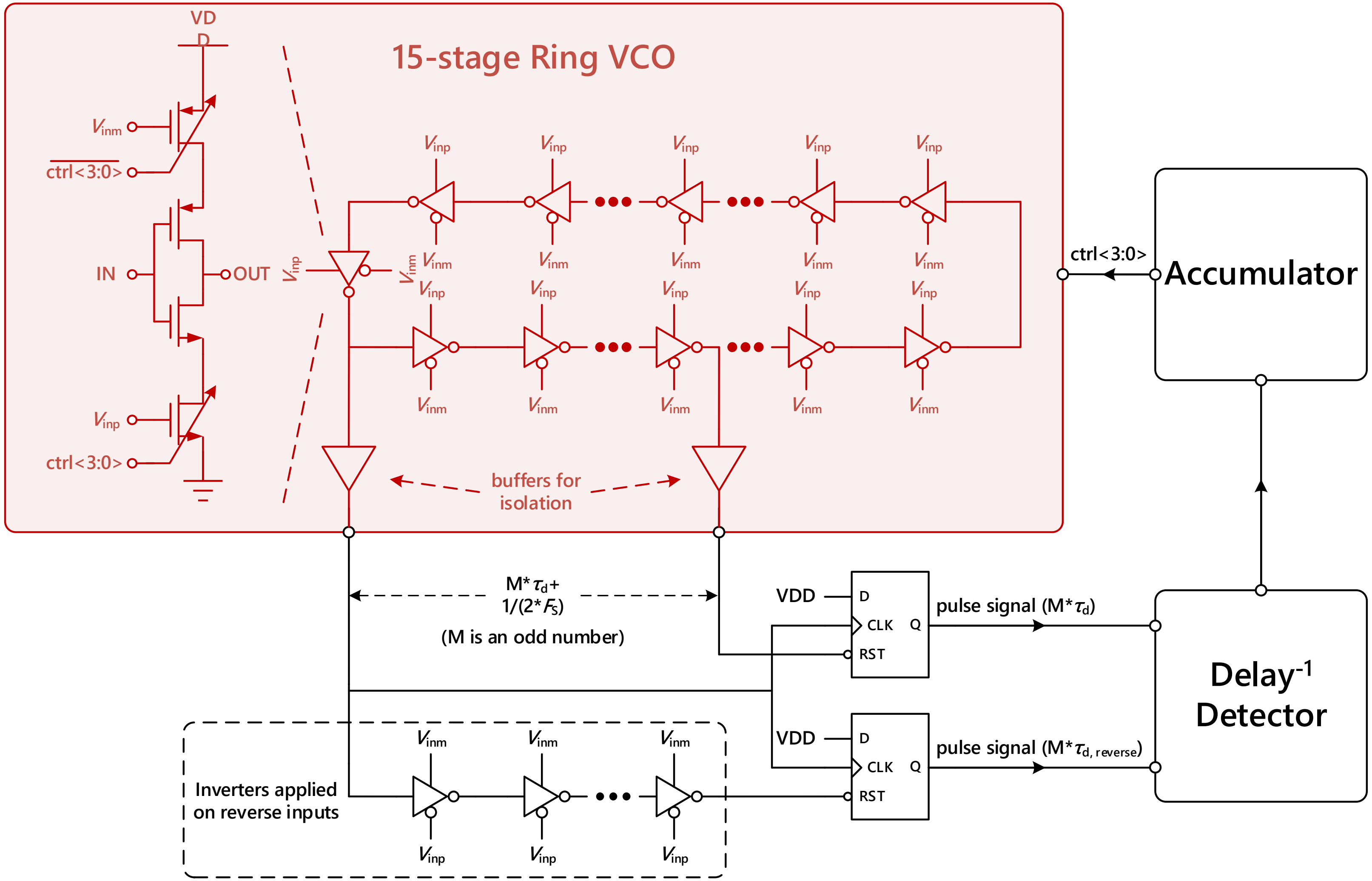
Ring VCO with the proposed calibration



Calibration Process

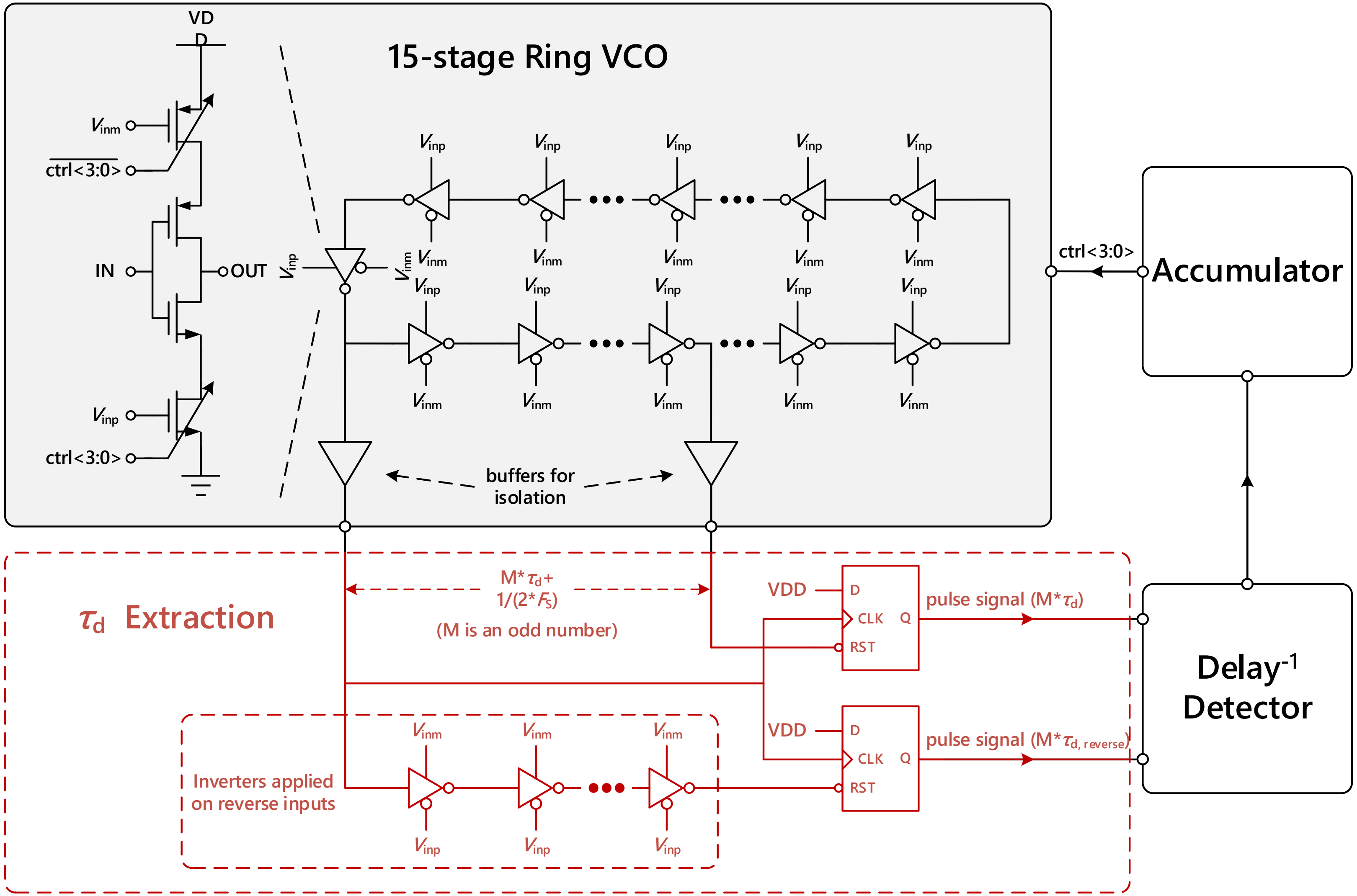
- 15-stage ring VCO
- τ_d extraction
- Delay^{-1} detector
- Accumulator
- 15-stage ring VCO

Ring VCO with the proposed calibration



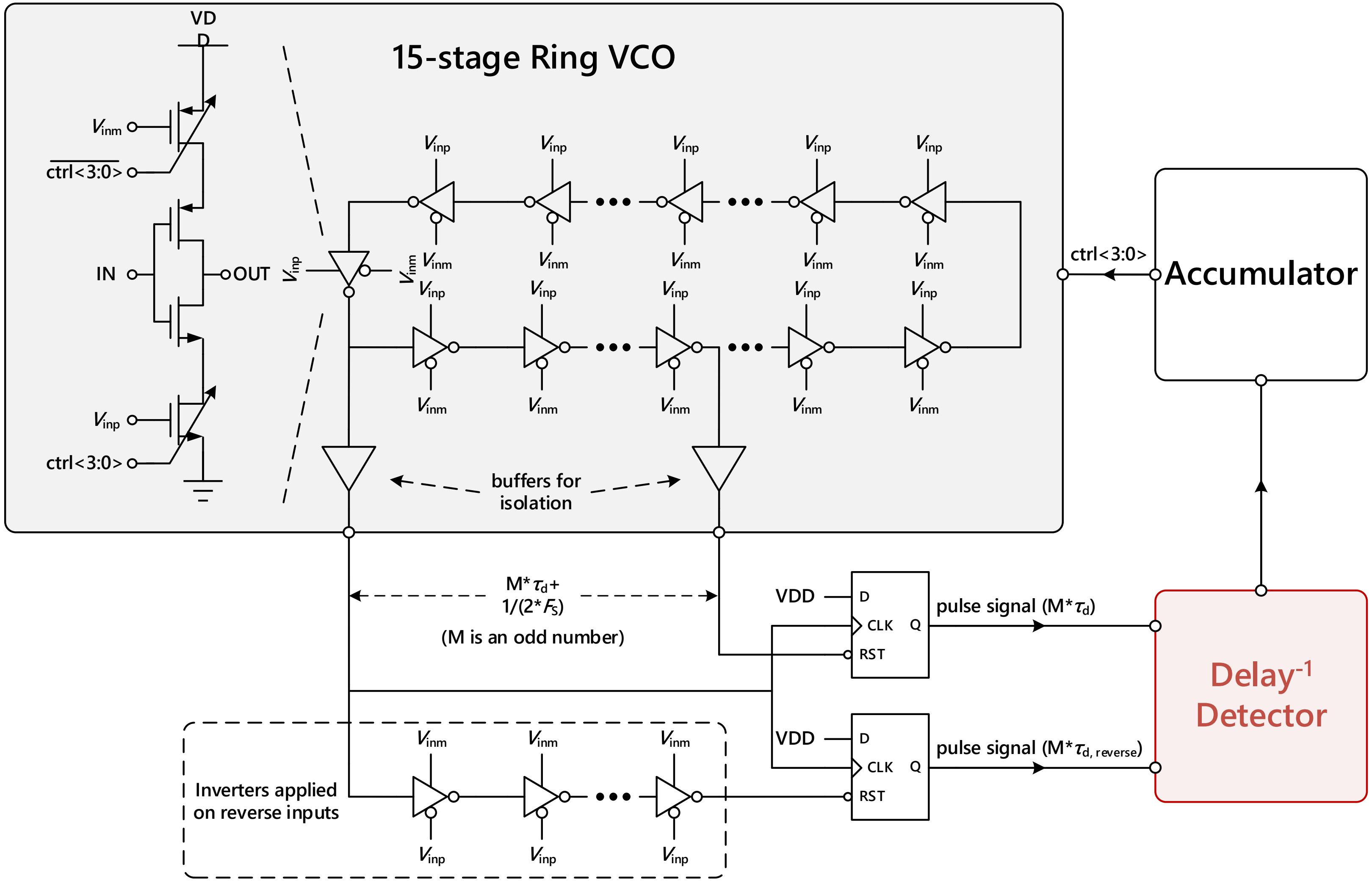
- **15-stage ring VCO**
  - Digital-biased tunable f_c
  - Output buffers for each stage
- **τ_d extraction**
- **Delay^{-1} detector**
- **Accumulator**

Ring VCO with the proposed calibration



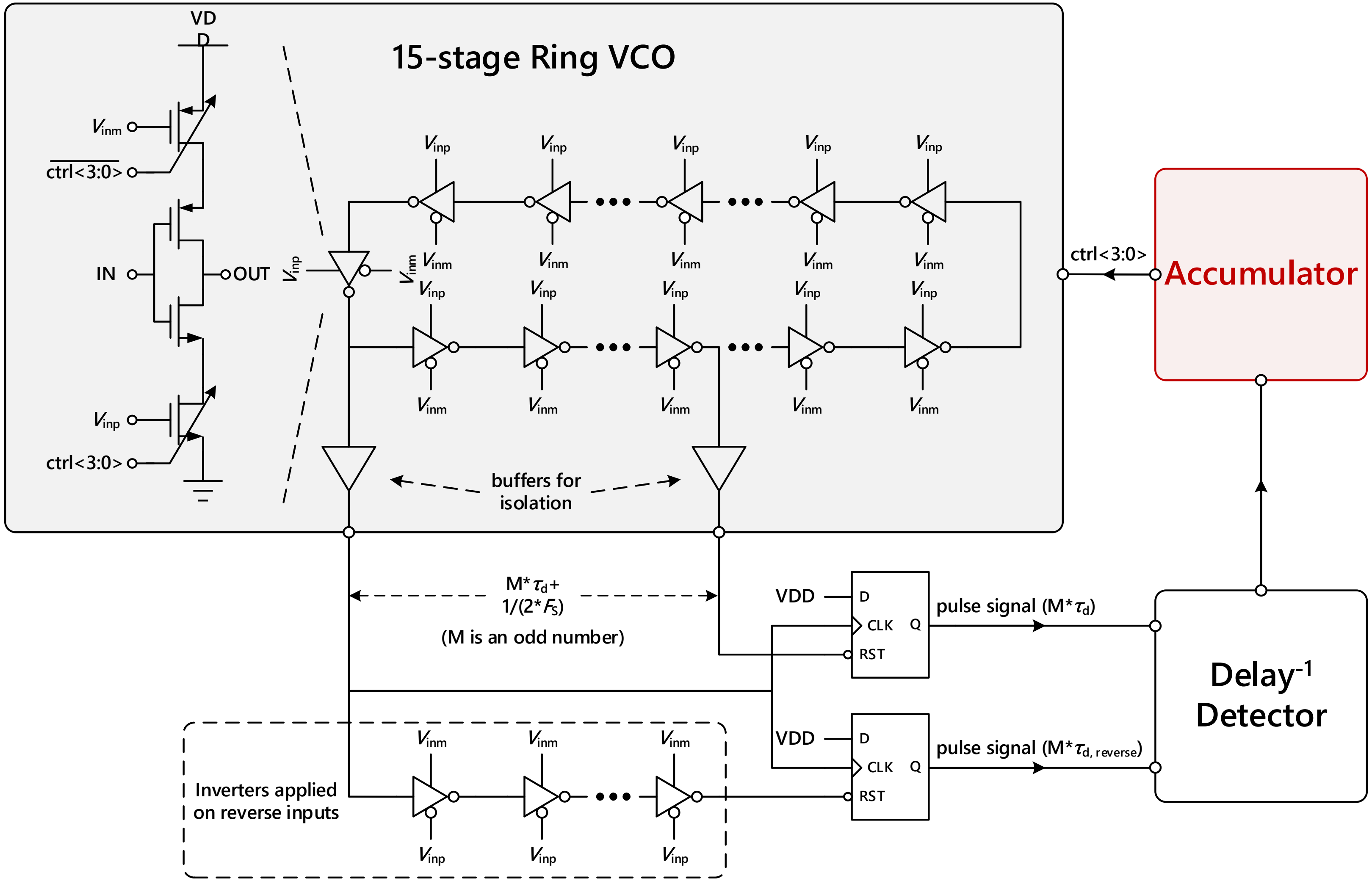
- **15-stage ring VCO**
- **τ_d extraction**
  - Only employs replica-inverters
  - Multi-τ_d for higher resolution
- **Delay^{-1} detector**
- **Accumulator**

Ring VCO with the proposed calibration



- **15-stage ring VCO**
- $\boldsymbol{\tau_d}$ **extraction**
- **Delay^{-1} detector**
  - Detecting using pulse signals
  - Detecting the τ_d^{-1} indirectly
- **Accumulator**

Ring VCO with the proposed calibration



- 15-stage ring VCO
- τ_d extraction
- Delay^{-1} detector
- Accumulator
  - Accumulating the detection results
  - Feeding back the digital-bias code

Proposed indirect delay^{-1} detection

- **Challenges**
  - **Avoiding division operations**
- **Reference generator**

$$V_{\text{out, normal}} = \frac{MI_{\text{ref}}}{C_{\text{ref}}} \cdot \tau_{\text{d}}$$

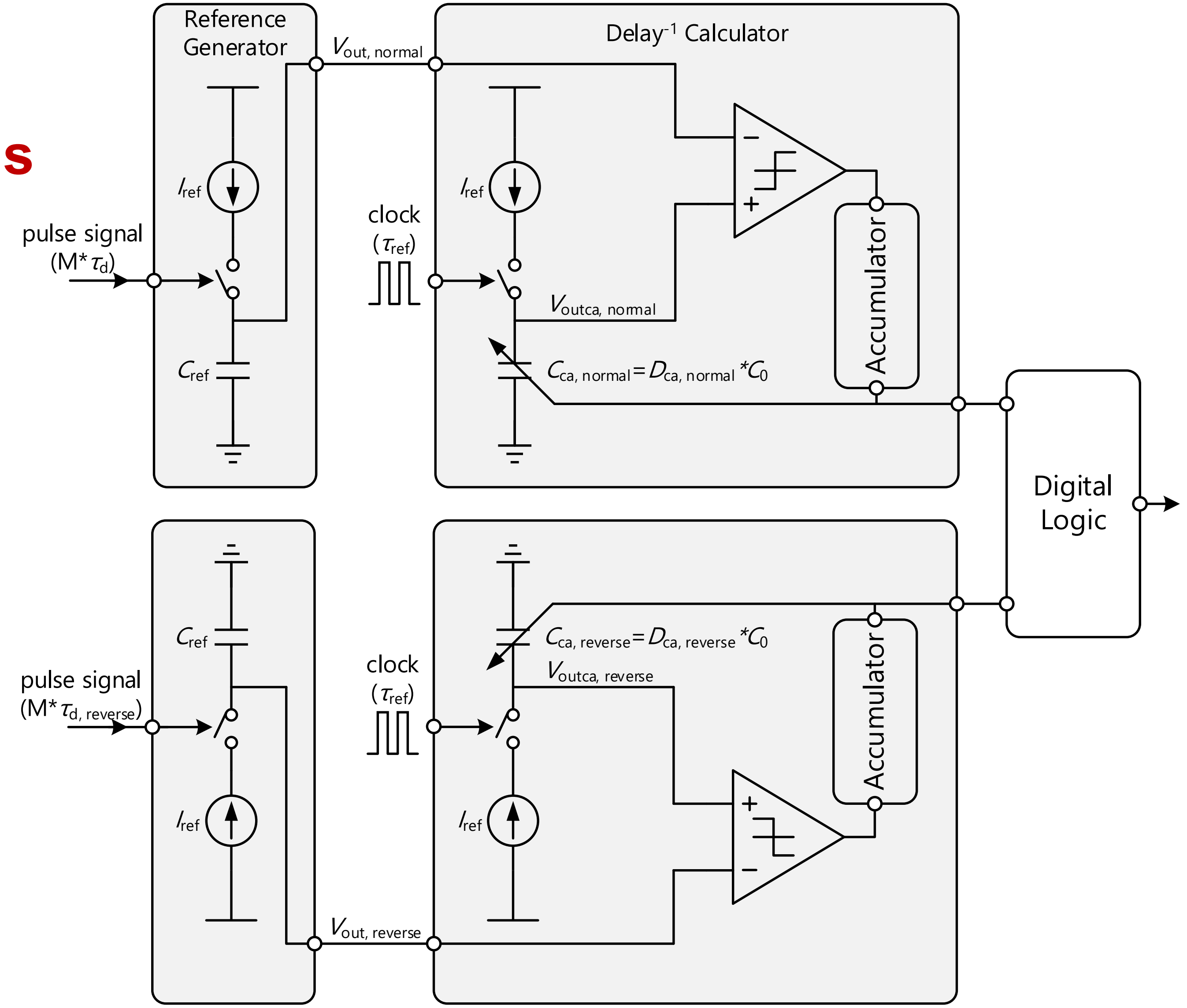
- **Producing equal voltage**

$$V_{\text{outca, normal}} = \frac{I_{\text{ref}}}{C_{\text{ca, normal}}} \cdot \tau_{\text{ref}}$$

τ_d^{-1} is represented by a digital code

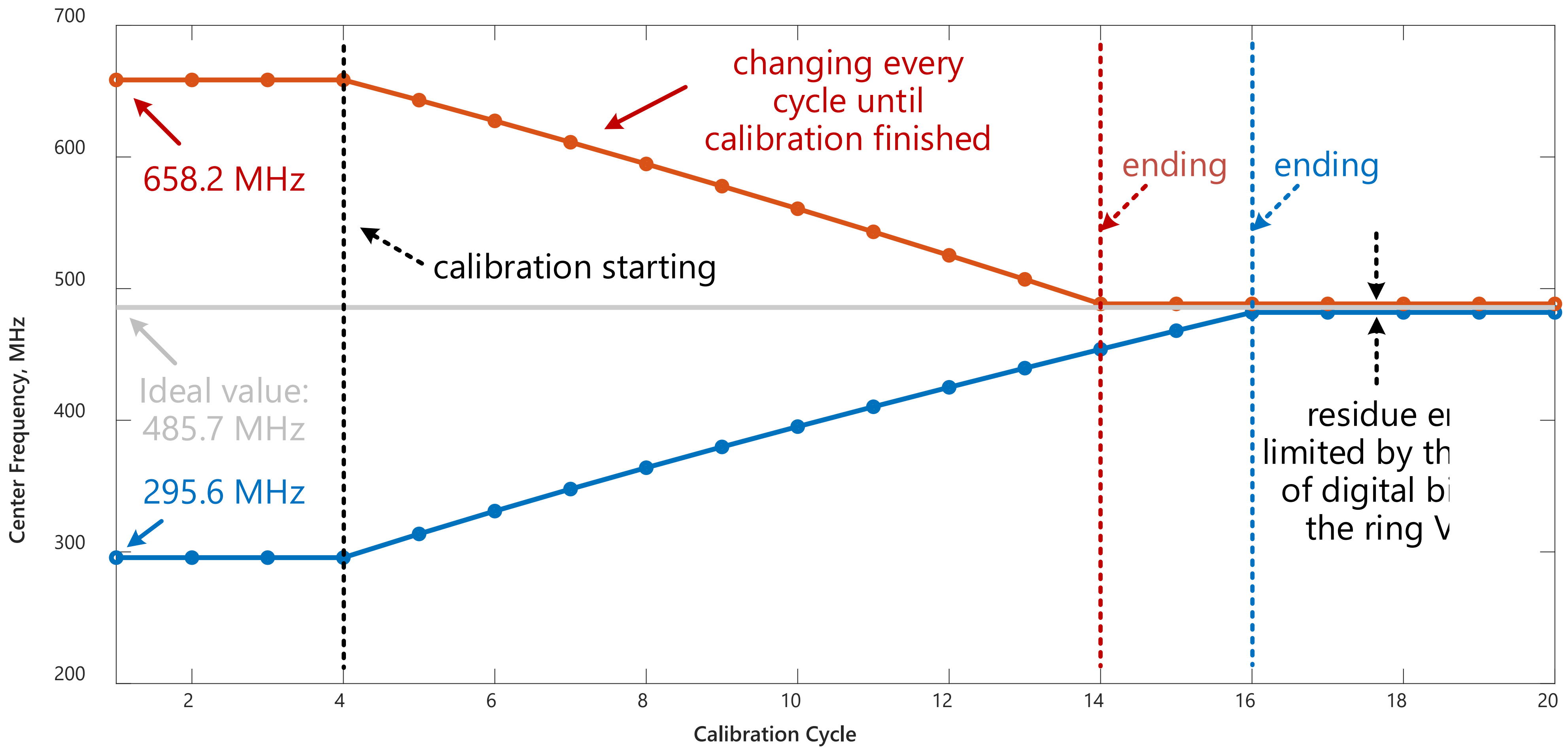
$$C_{\text{ca, normal}} = \frac{C_{\text{ref}} \cdot \tau_{\text{ref}}}{M \cdot \tau_{\text{d}}}$$

$$D_{\text{ca, normal}} = \frac{C_{\text{ref}} \cdot \tau_{\text{ref}}}{M \cdot C_0 \cdot \tau_{\text{d}}}$$



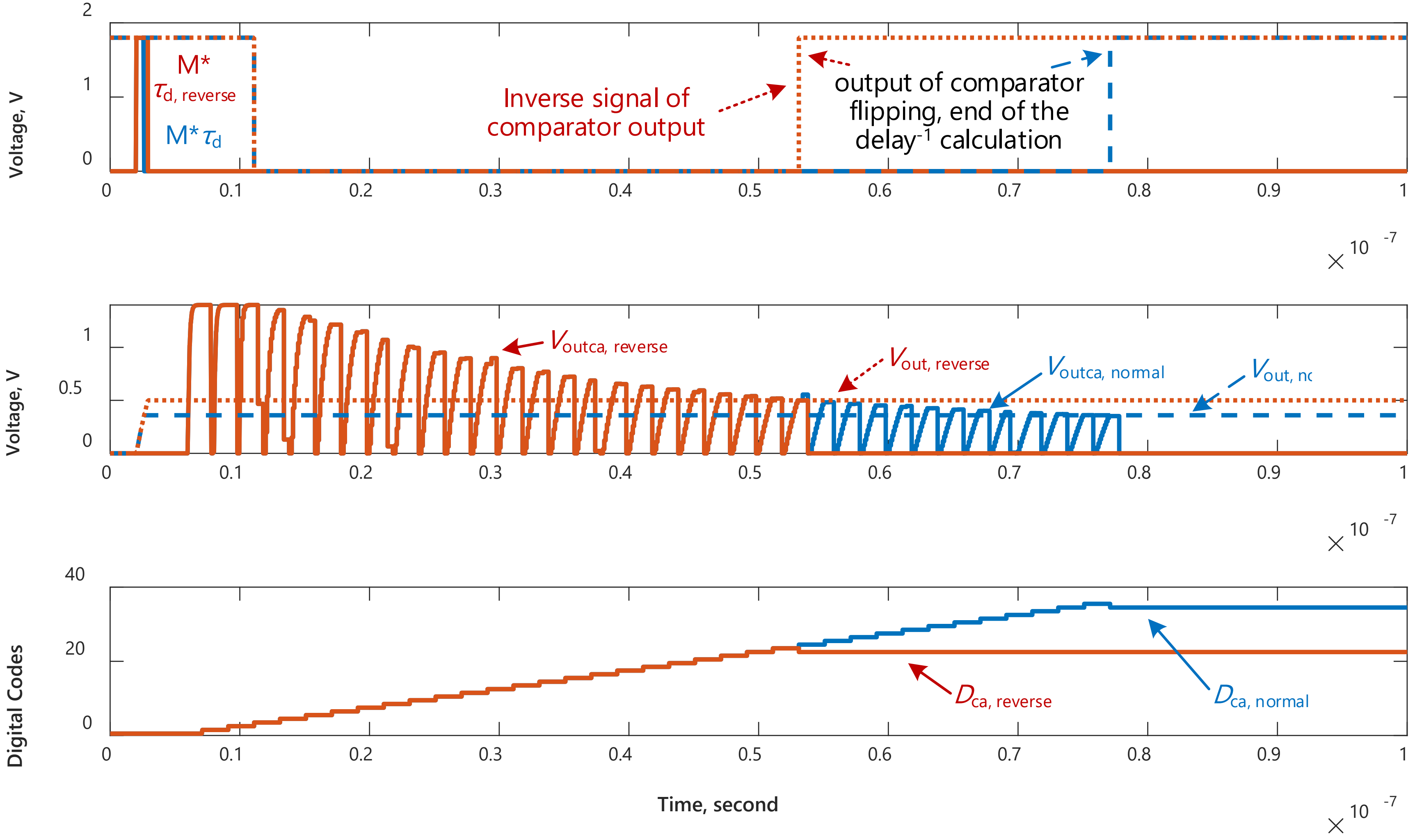
Simulation results——a 15-stage ring VCO in 180nm CMOS

- **Correction process of the deviated center frequency**



Simulation results——a 15-stage ring VCO in 180nm CMOS

- **Signals in the delay-1 detector in one calibration cycle**



Conclusion

- **A center frequency calibration technique is proposed for ring VCO**
  - Only delay information is employed
  - No replica-VCOs or signal paths
  - Calibration by applying reverse signals
  - High hardware-efficiency

- **An indirect delay^{-1} detection method**
  - Avoiding complex division operation
  - Detecting exploiting a reference clock and a comparator

- **A 15-stage ring VCO in 180nm CMOS with the proposed calibration**
  - Deviated center frequency is corrected step by step