RMO1B

# A Multiphase PWM RF Modulator Using a VCO-Based Opamp in 45nm CMOS

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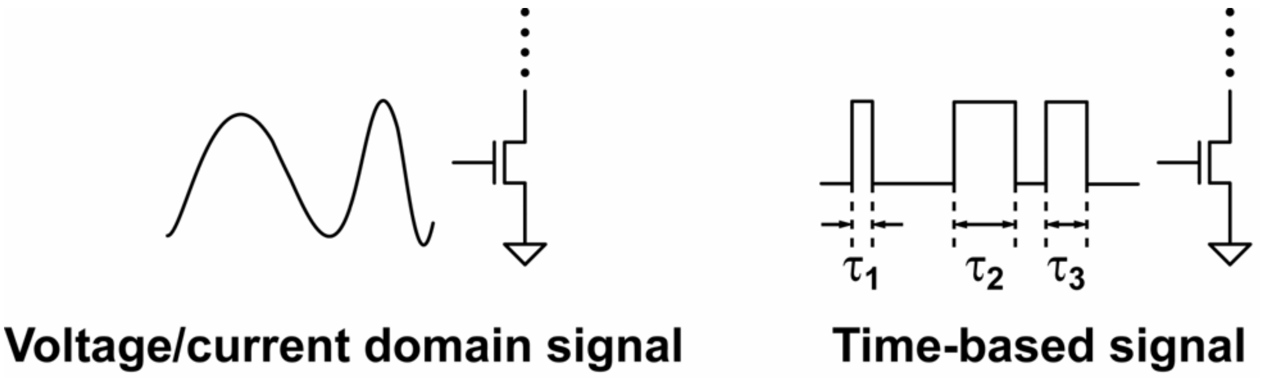
RFIC – Anaheim May 23-25, 2010

## *Motivation*

- There has been much interest in achieving analog functionality with reduced analog design effort
- One promising approach is using *time* as a primary signal domain

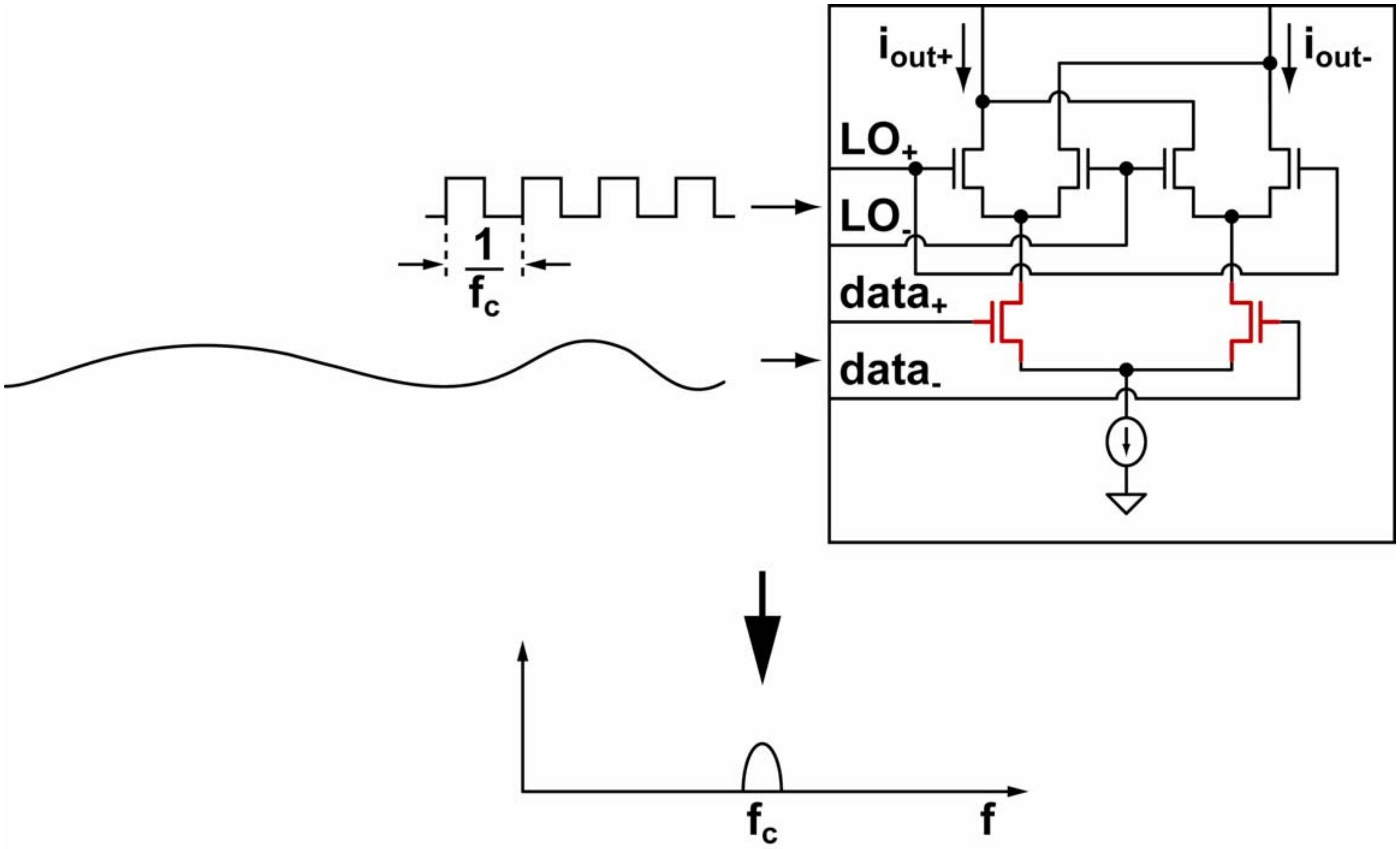



- We will consider this approach in the context of an RF modulator targeting wireless LAN specifications.

## *Outline*

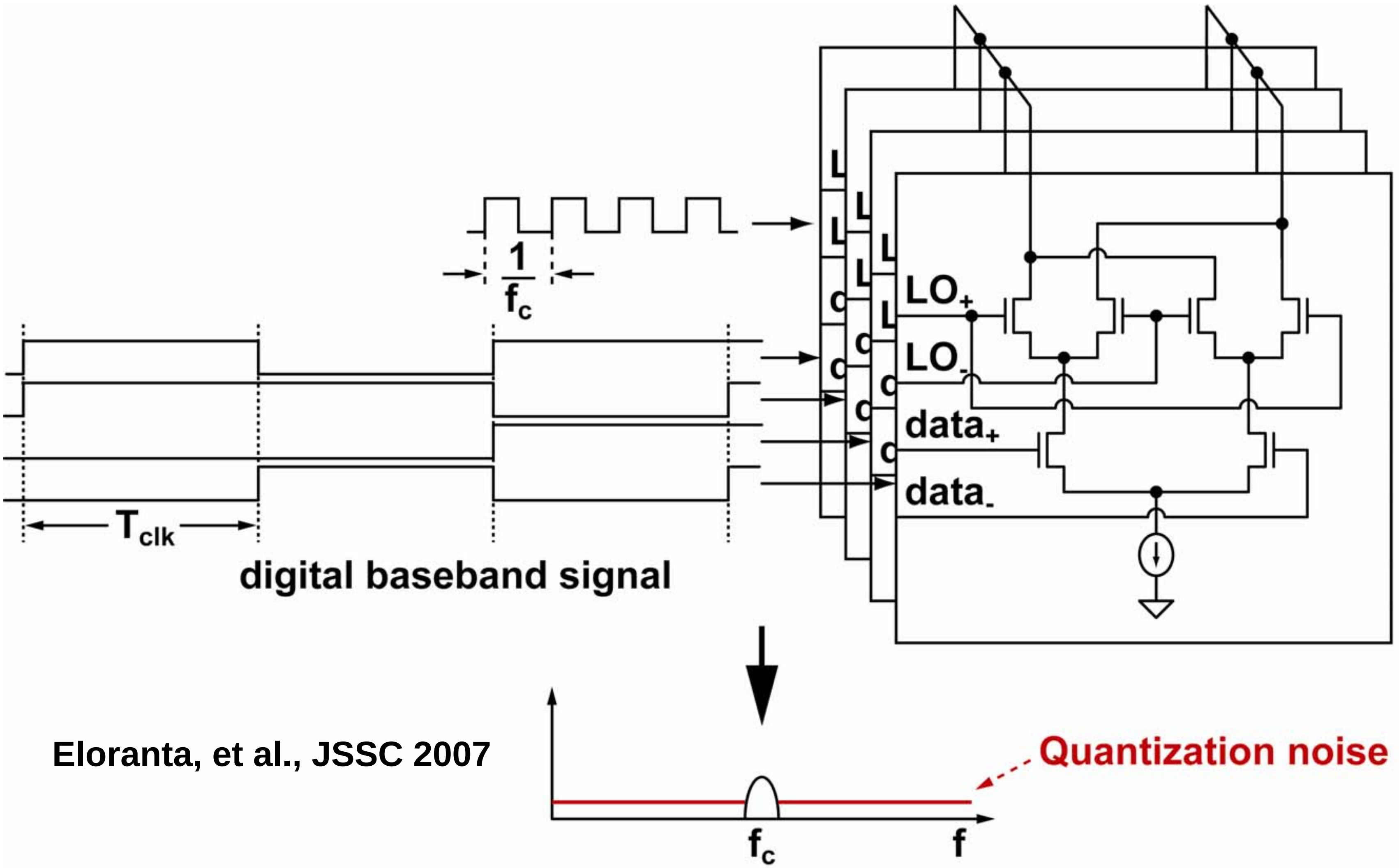
- Comparison of various RF modulation schemes
- RF modulator employing multiphase PWM
- VCO-based opamp
- Proposed multiphase PWM RF modulator
- Measurement results
- Summary

# *Driving a Gilbert cell with an Analog Signal*



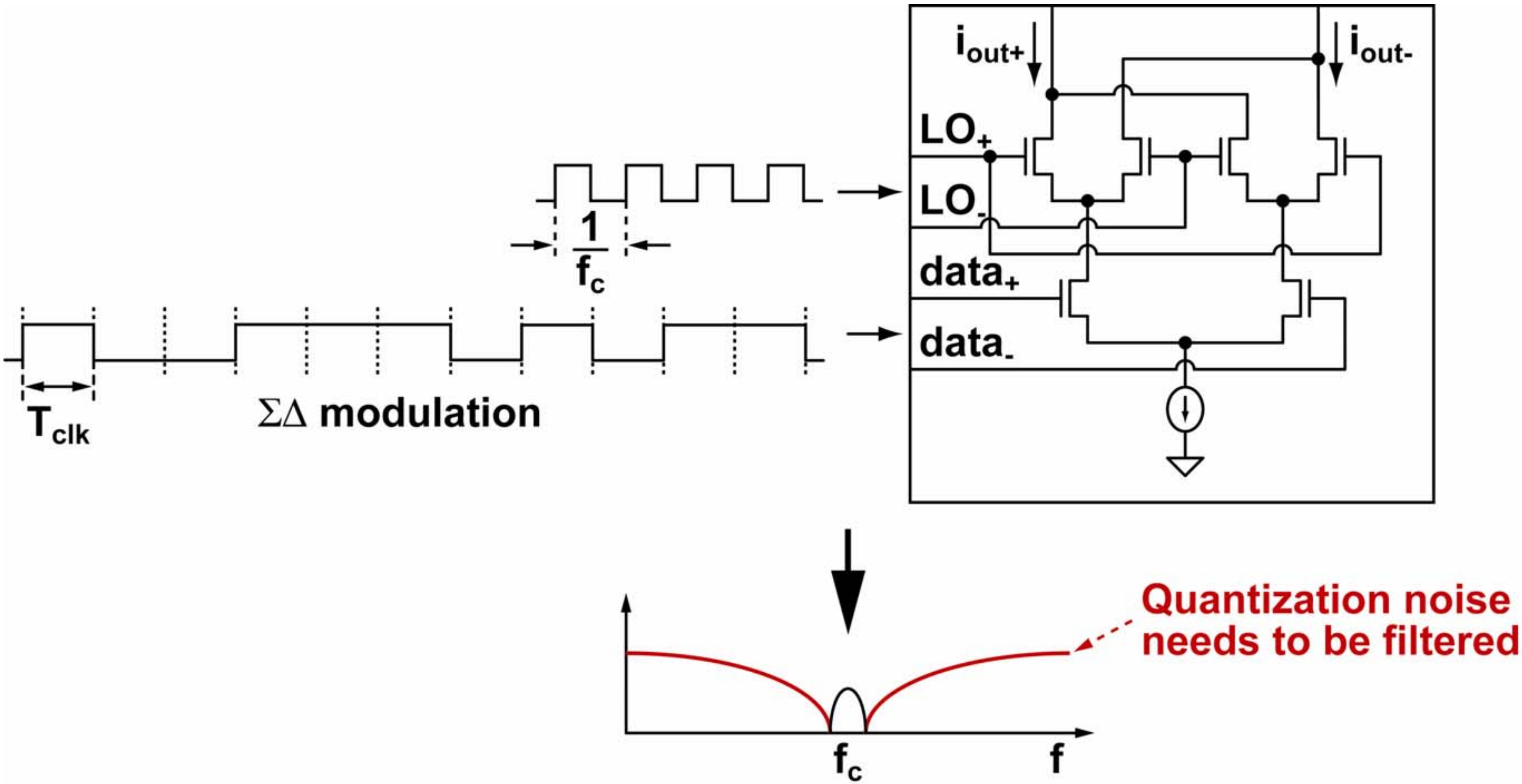

- **Requires linear transconductors**
  - **Avoiding linear transconductors helps to reduce analog complexity**

# *RFDAC*




- The resolution is limited by device mismatch

## *RFDAC with ΣΔ modulation*

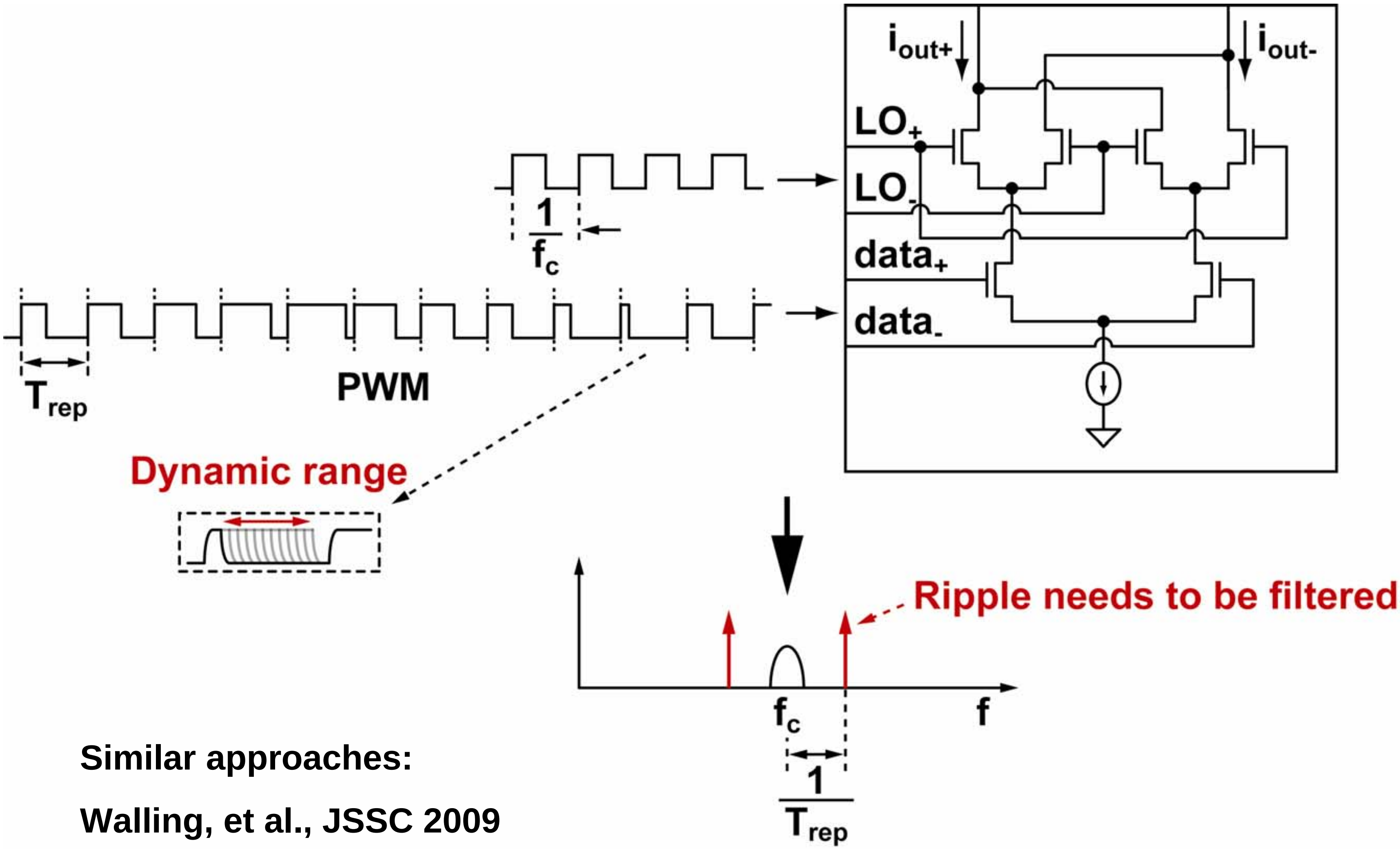



Jerng, Sodini, JSSC 2007

Taleie, et al., RFIC 2008

- **Out-of-band quantization noise needs to be filtered**

# *Up-conversion Using Single-Phase PWM*

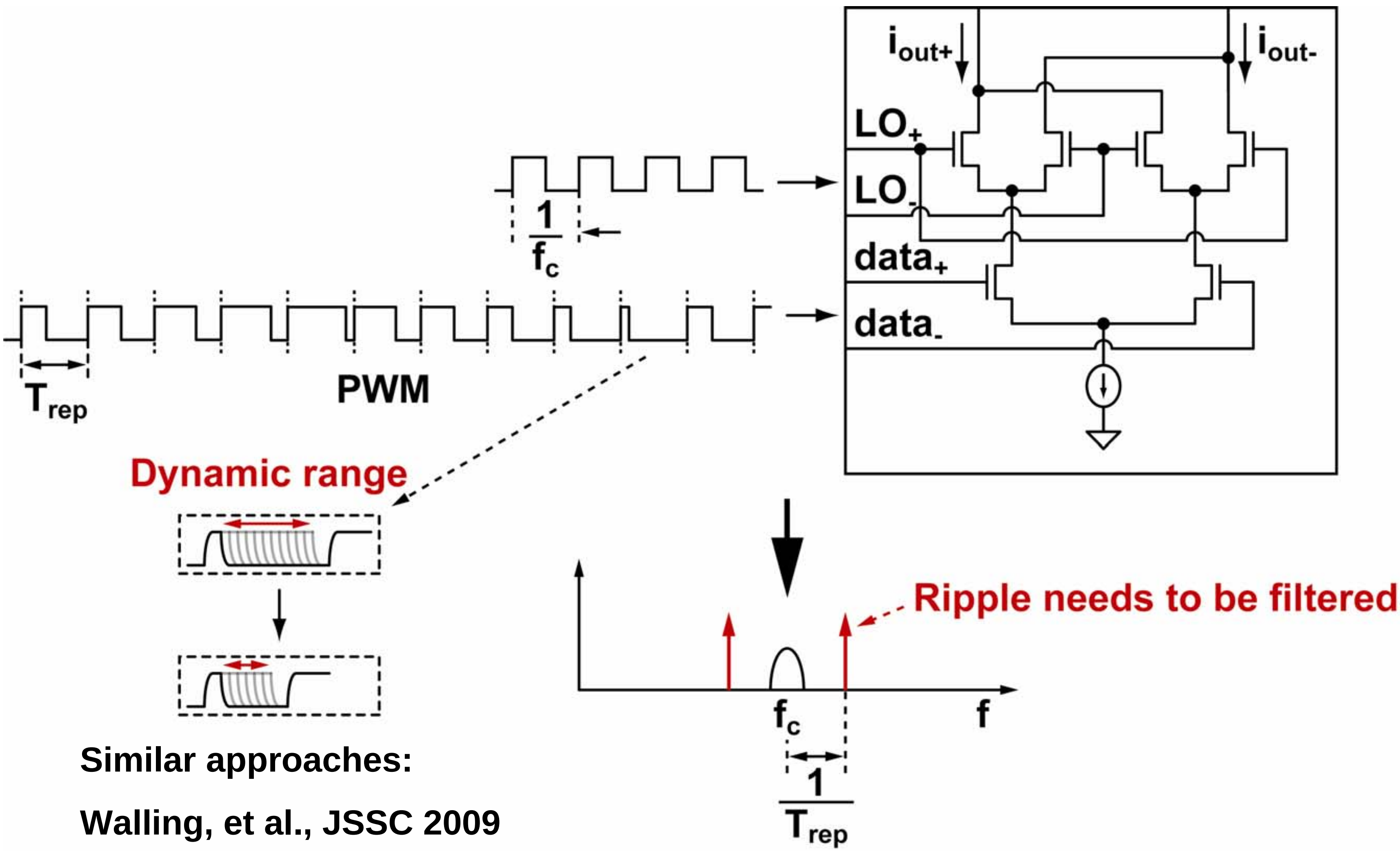



**Similar approaches:**

**Walling, et al., JSSC 2009**

- **Key trade-off : ripple frequency versus dynamic range**

# *Up-conversion Using Single-Phase PWM*



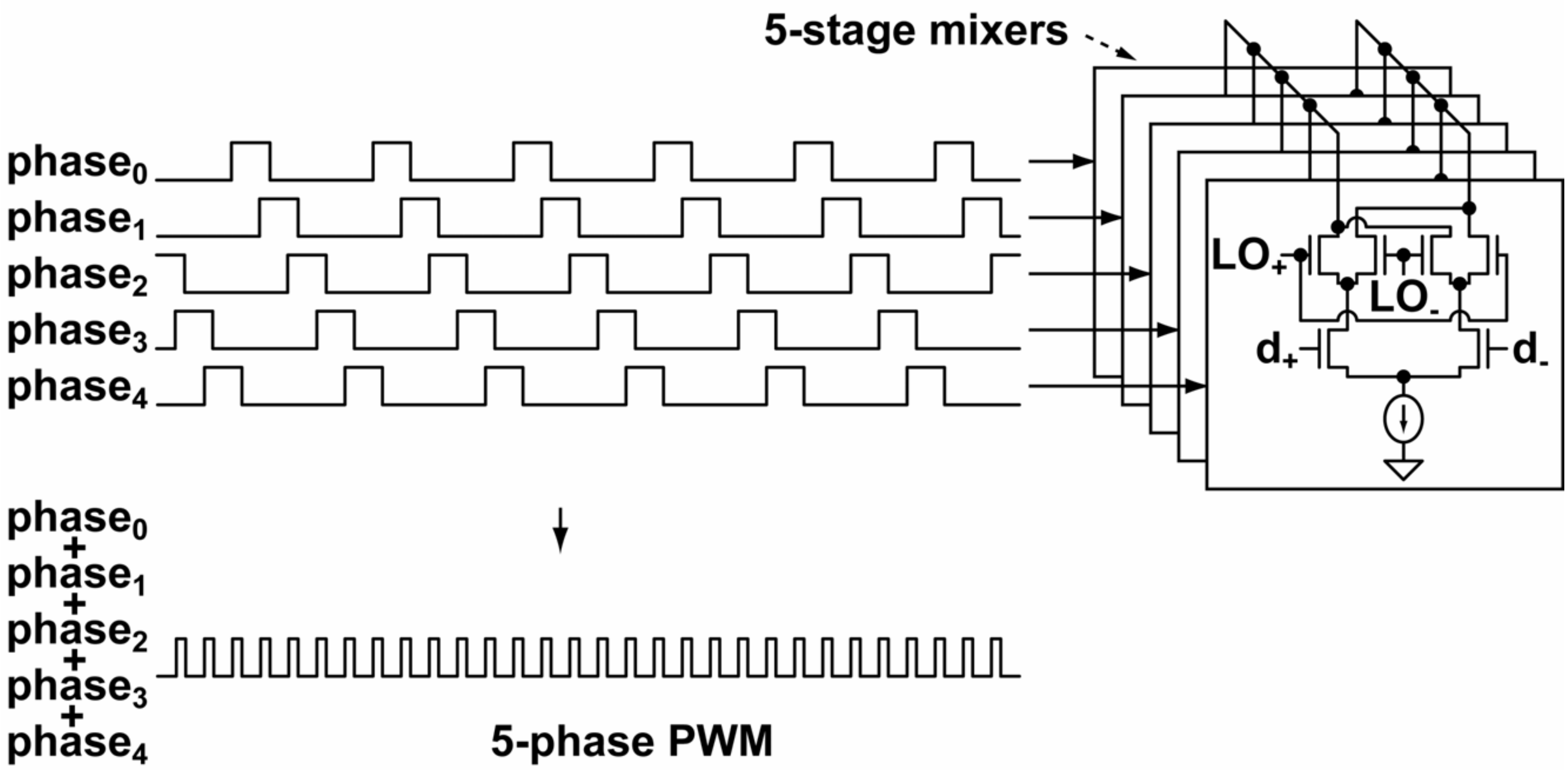

**Similar approaches:**

**Walling, et al., JSSC 2009**

- **Key trade-off : ripple frequency versus dynamic range**

**Can we improve the trade-off between the ripple frequency and the dynamic range of PWM?**

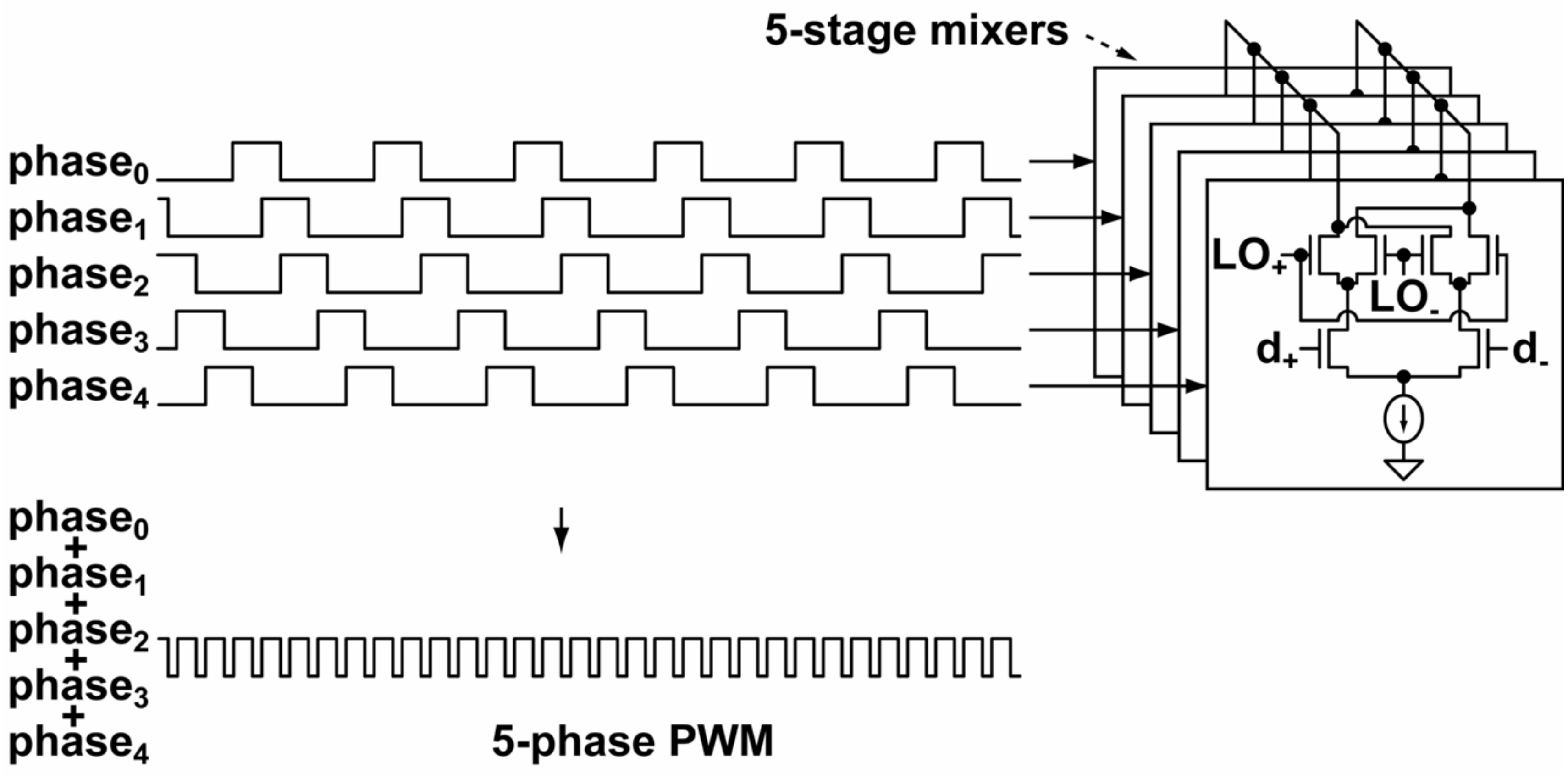
# Proposed Multi-Phase PWM RF Modulator



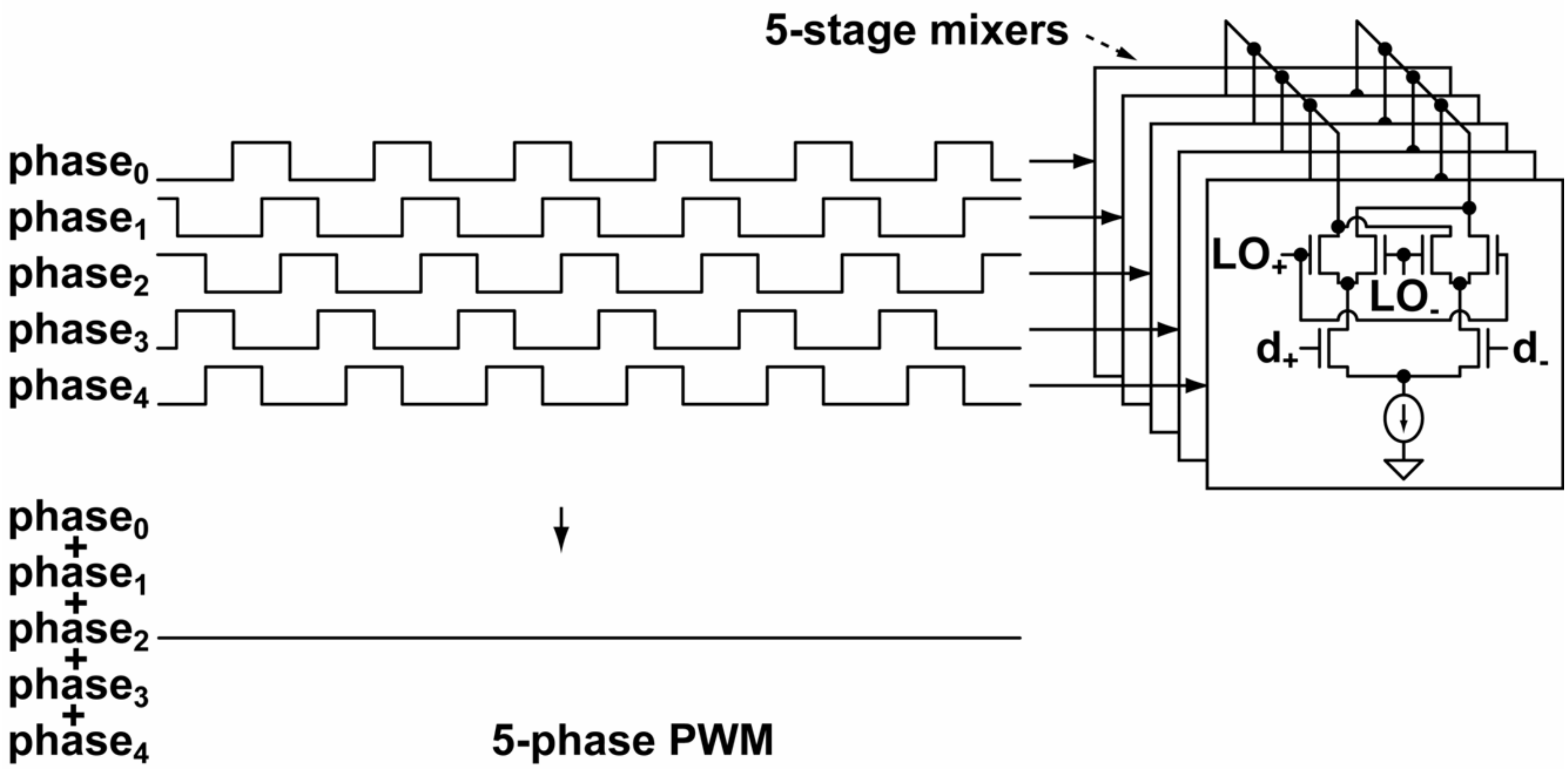

**Similar approaches:**

**Weaver, Trans. Broadcasting, 1992**

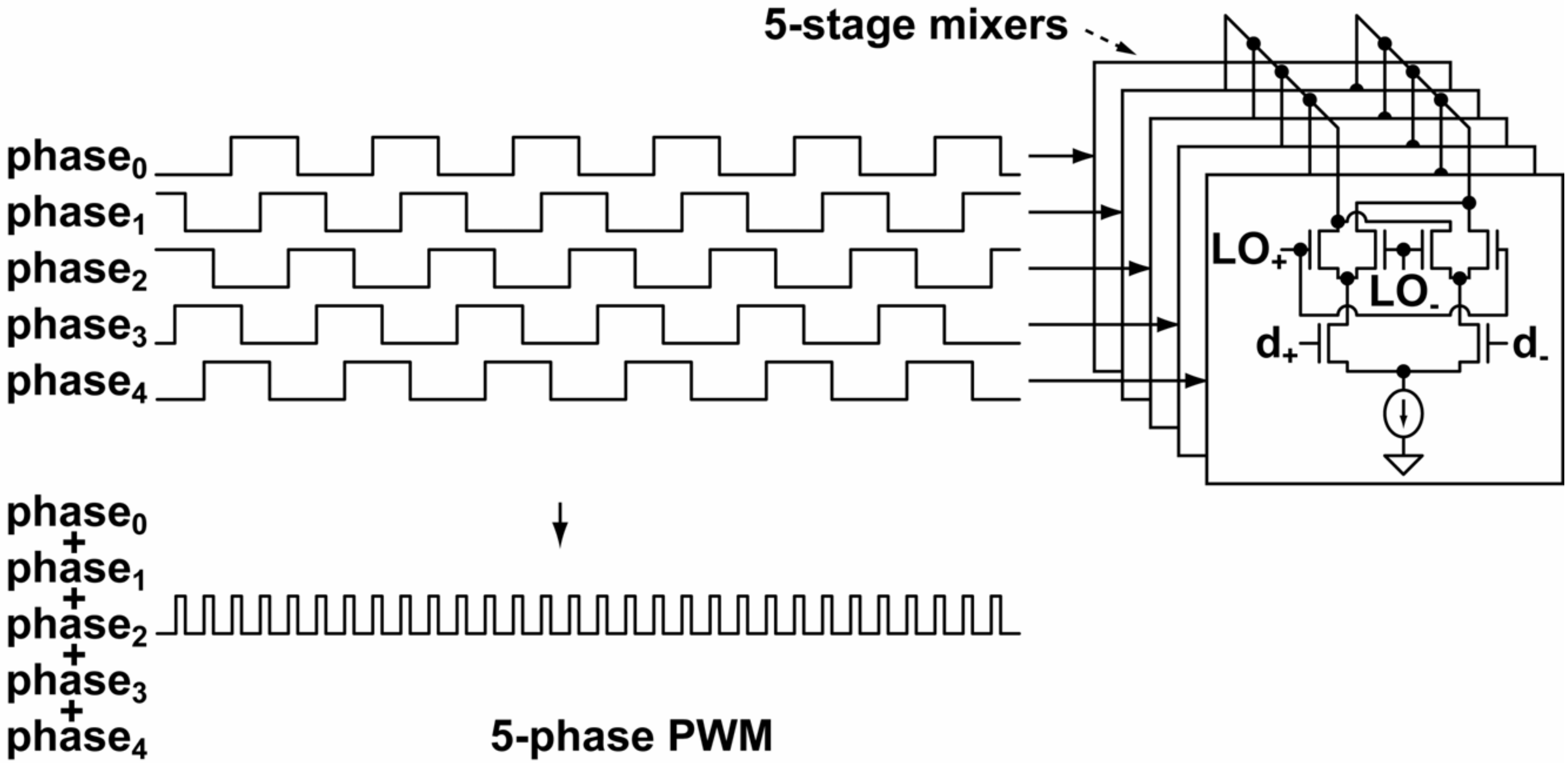
# *Impact of Phase Adjustment (1)*



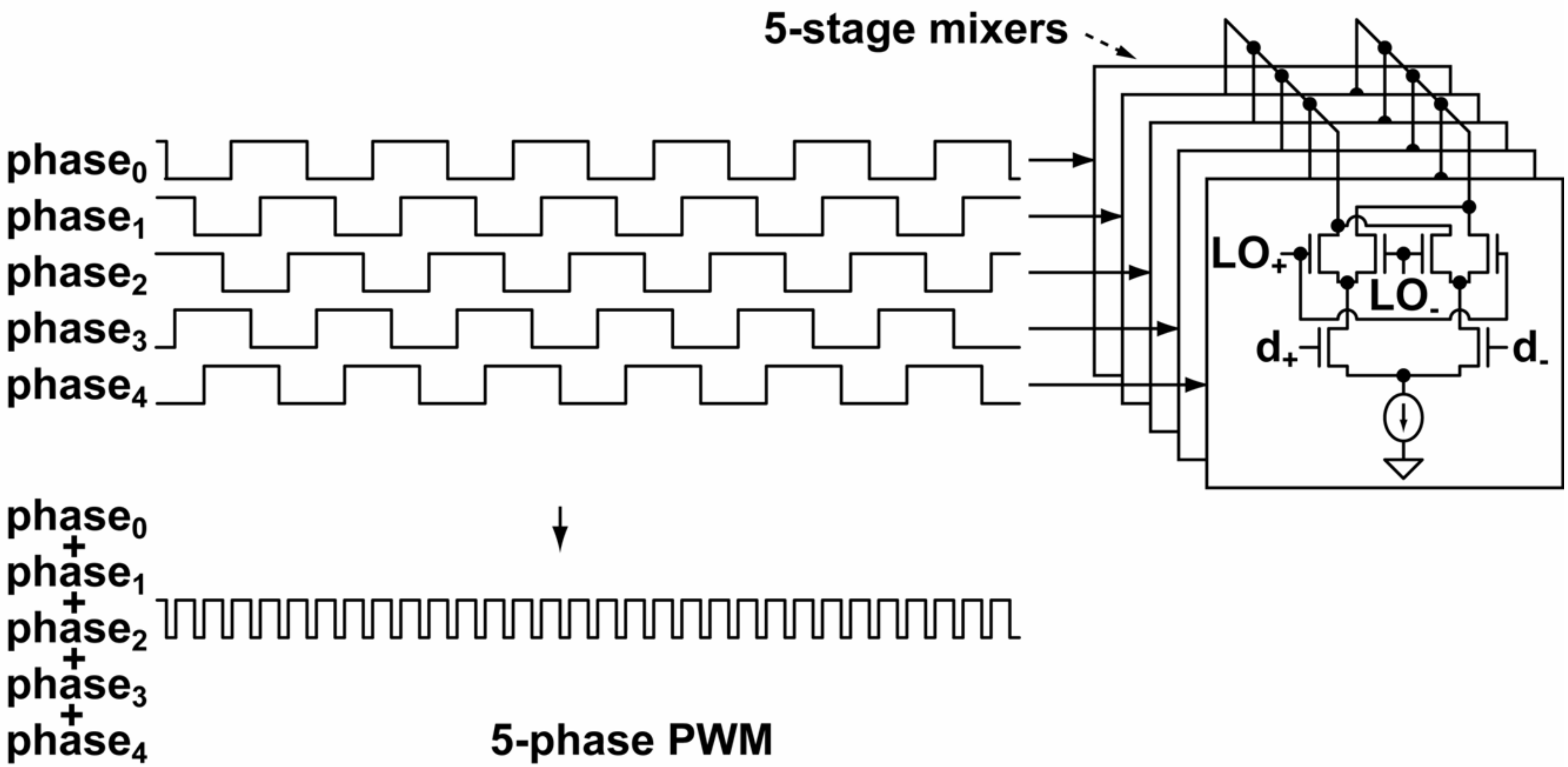
# *Impact of Phase Adjustment (2)*



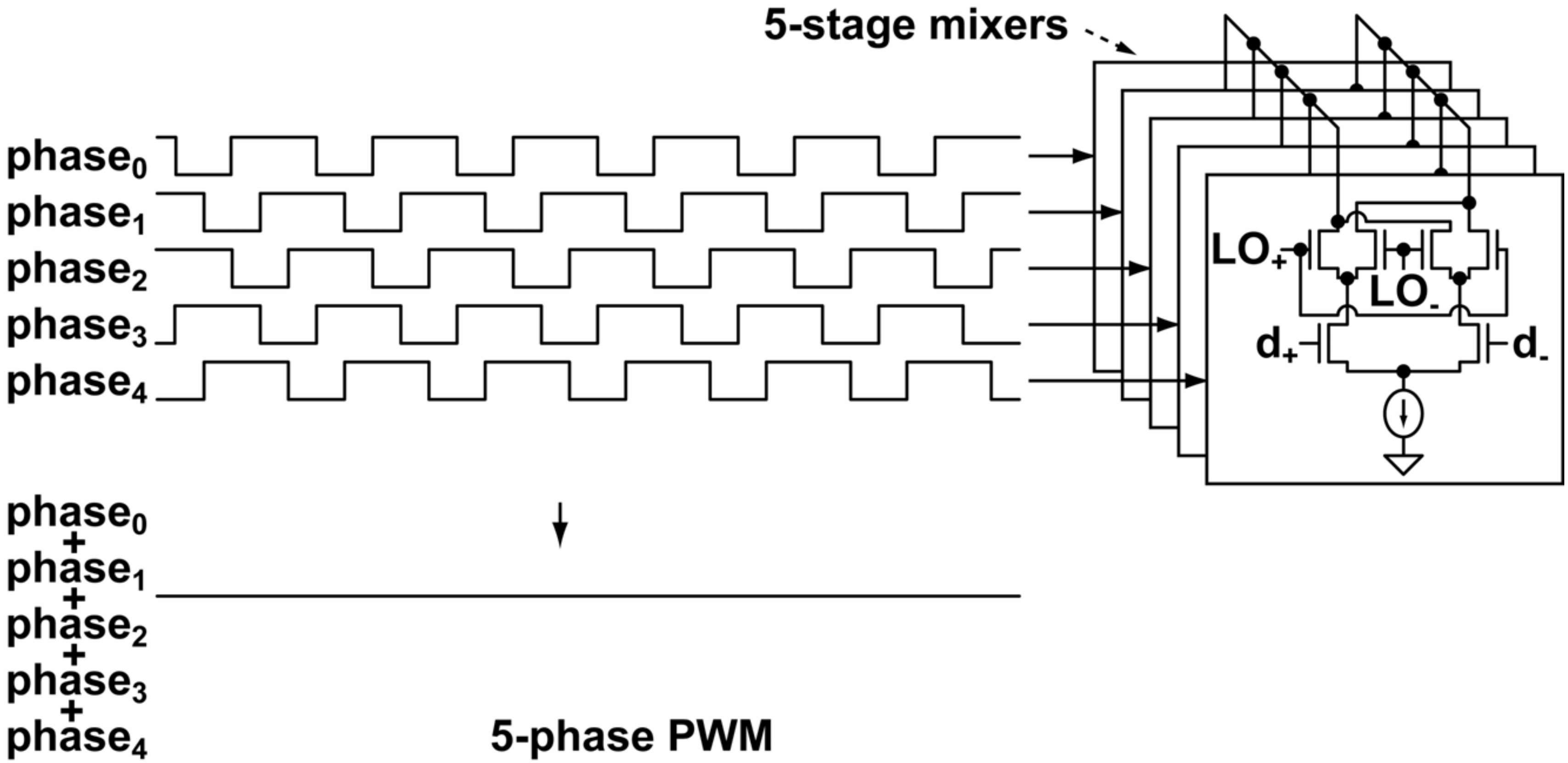
# *Impact of Phase Adjustment (3)*



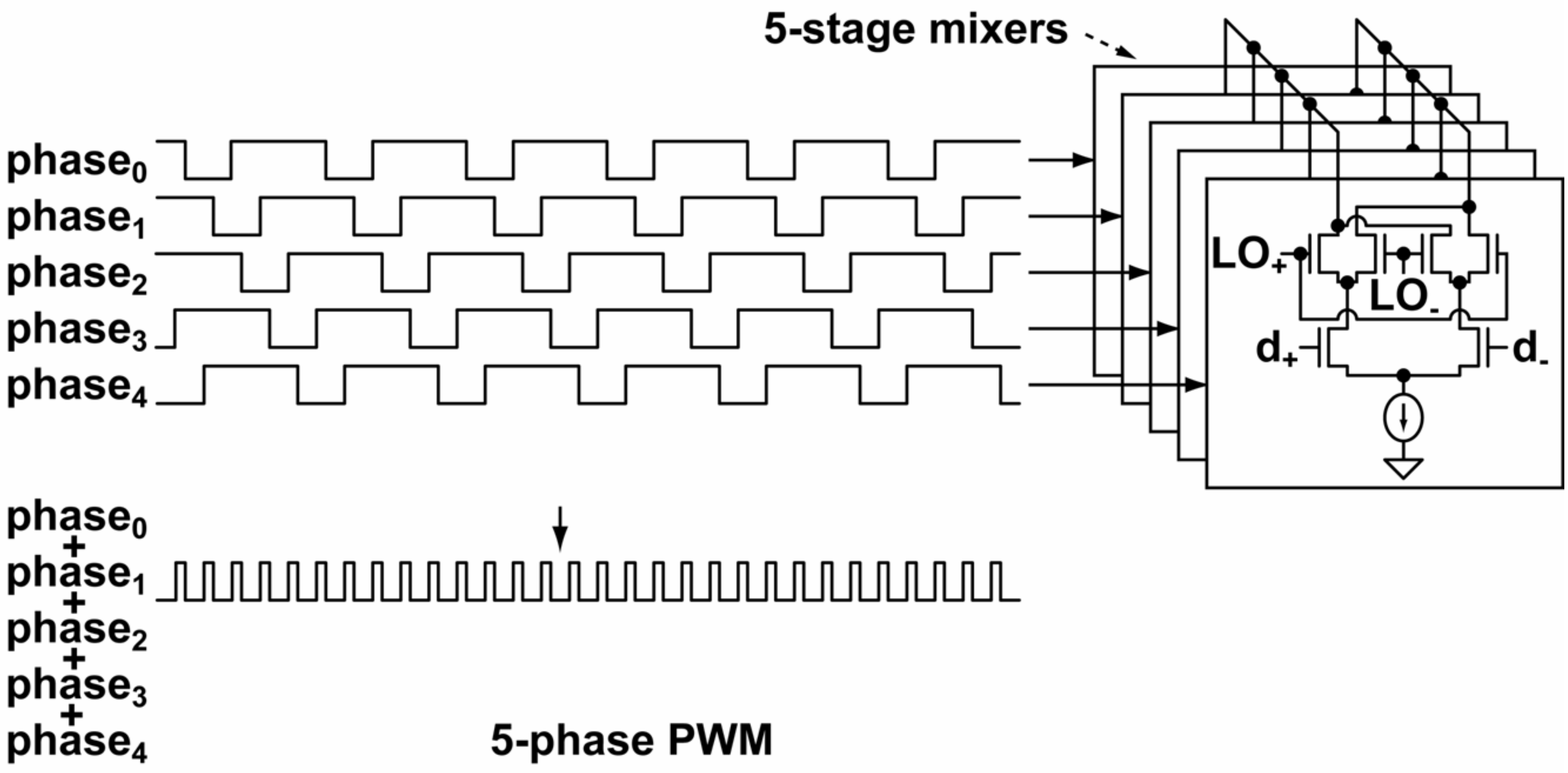
# Impact of Phase Adjustment (4)



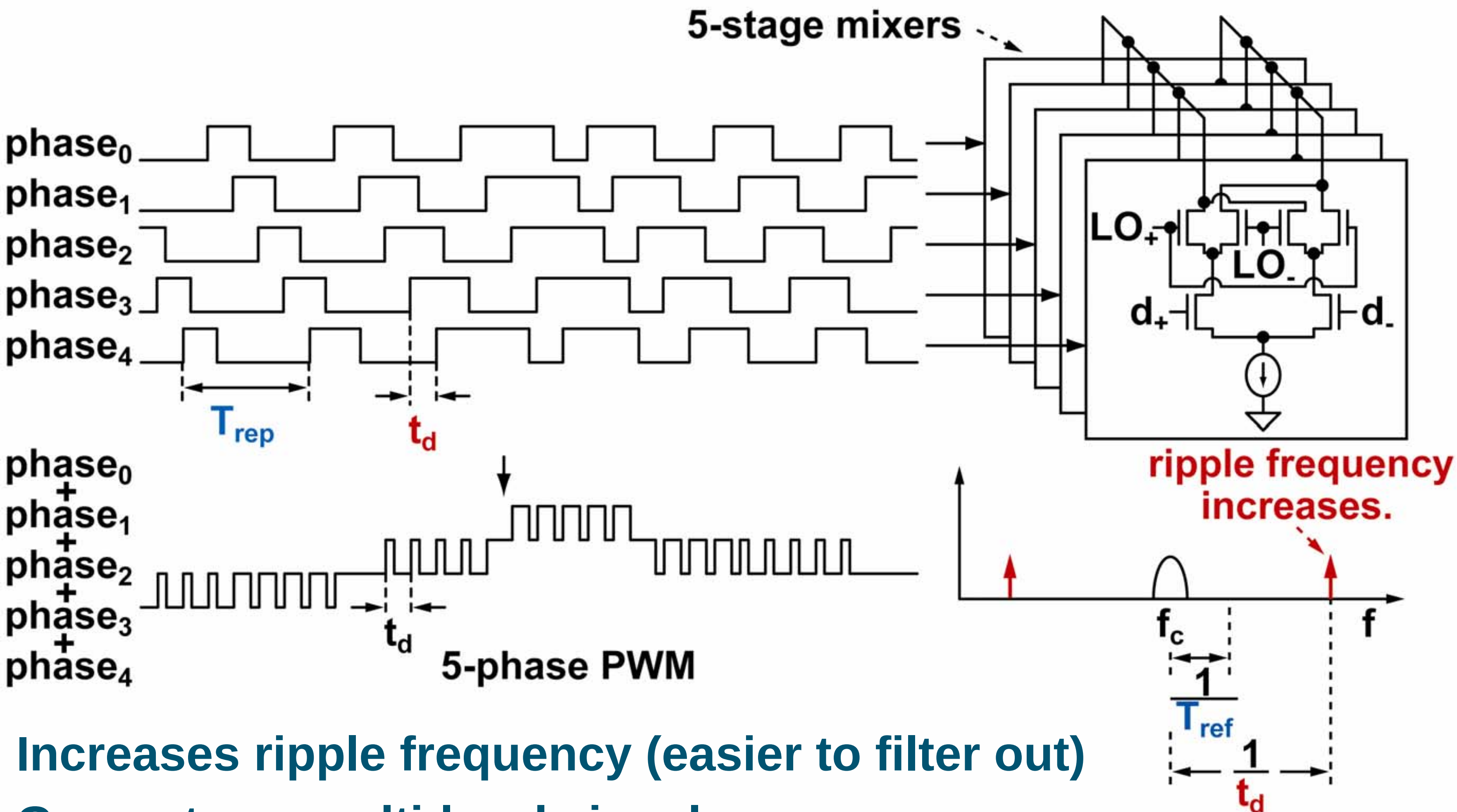
# Impact of Phase Adjustment (5)



# *Impact of Phase Adjustment (6)*

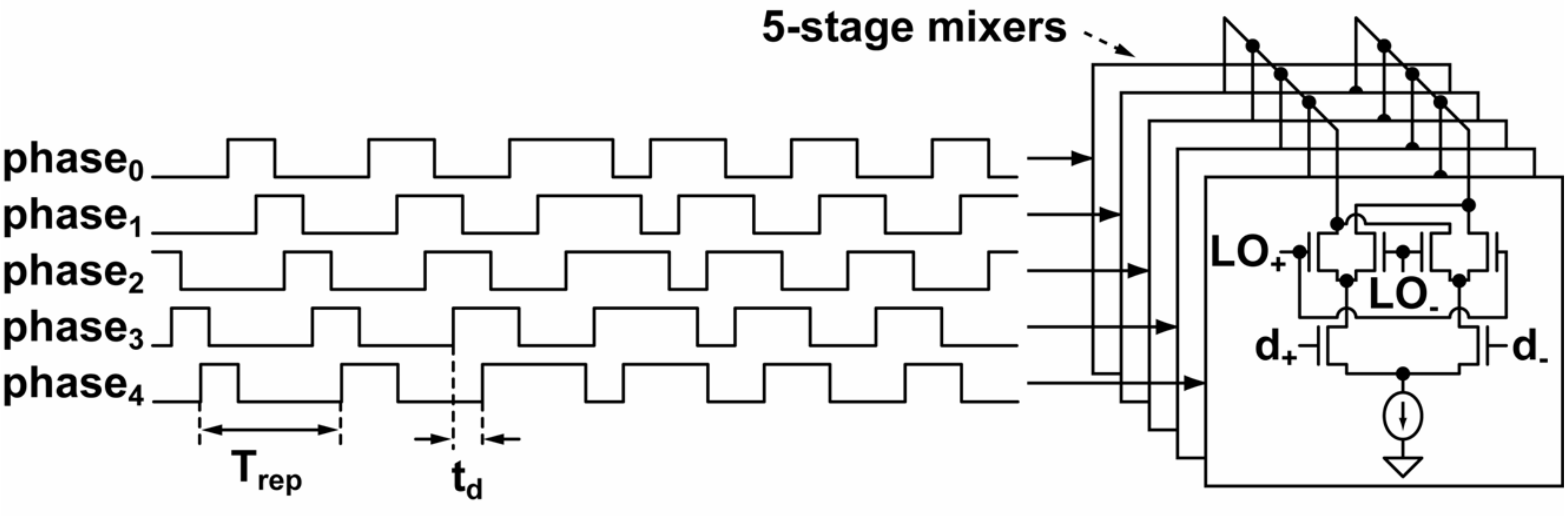


# *Benefits of the Proposed Approach*



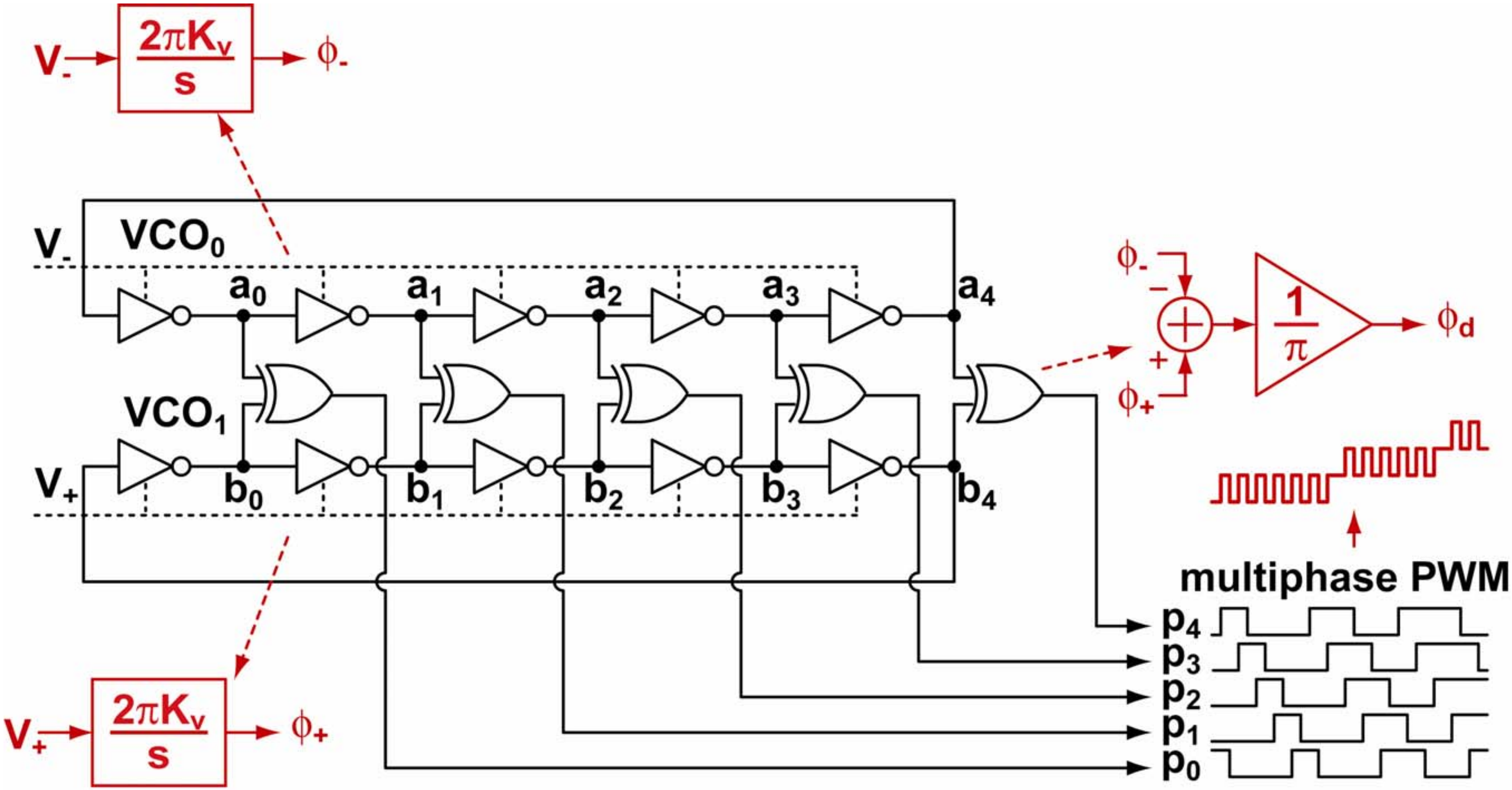

- Increases ripple frequency (easier to filter out)
- Generates a multi-level signal
  - Increases dynamic range
  - Decreases relative ripple amplitude

## *Key Implementation Issue*

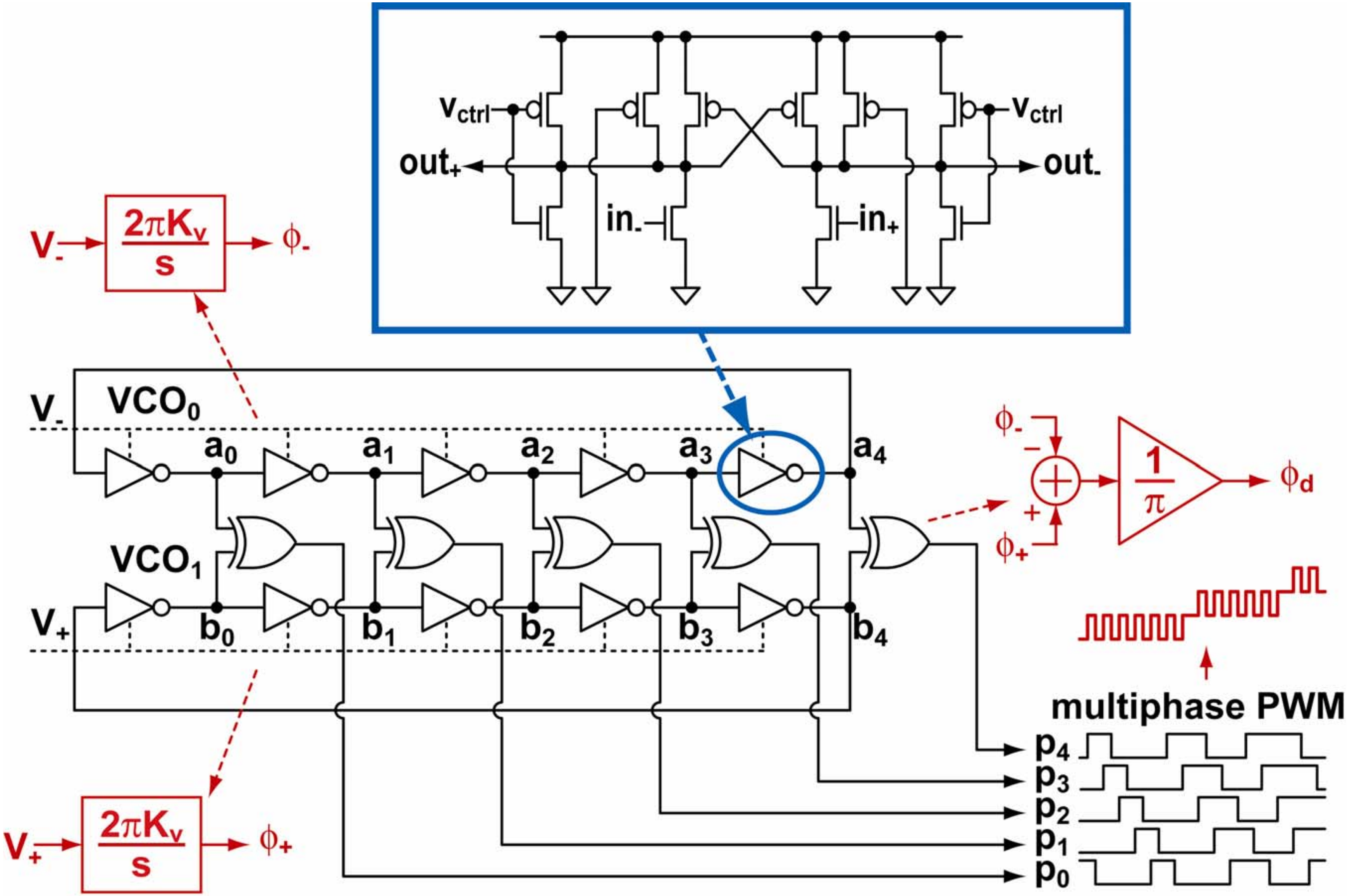



**How do we create multiphase PWM signals?**

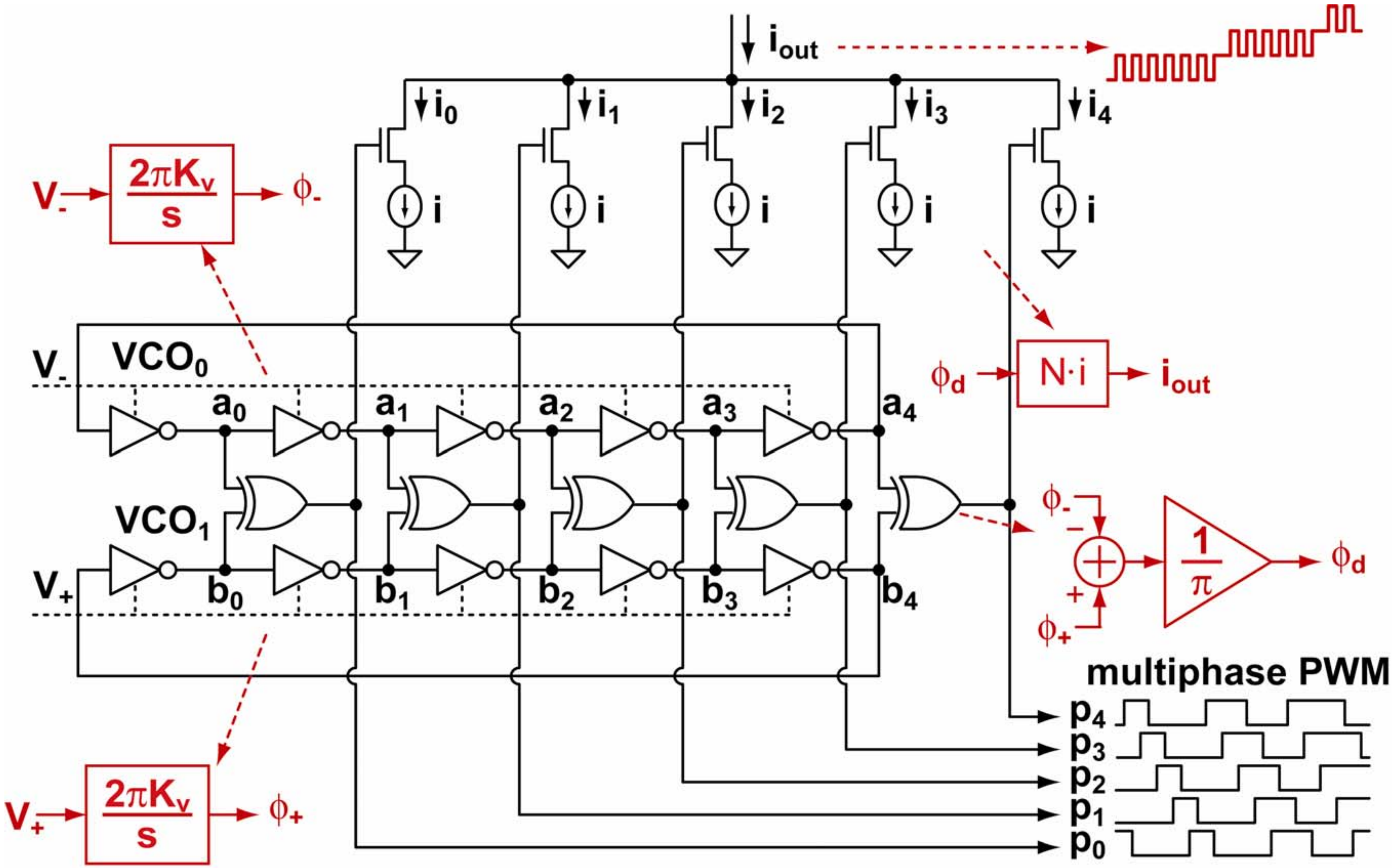
# Proposed Multi-Phase PWM generator



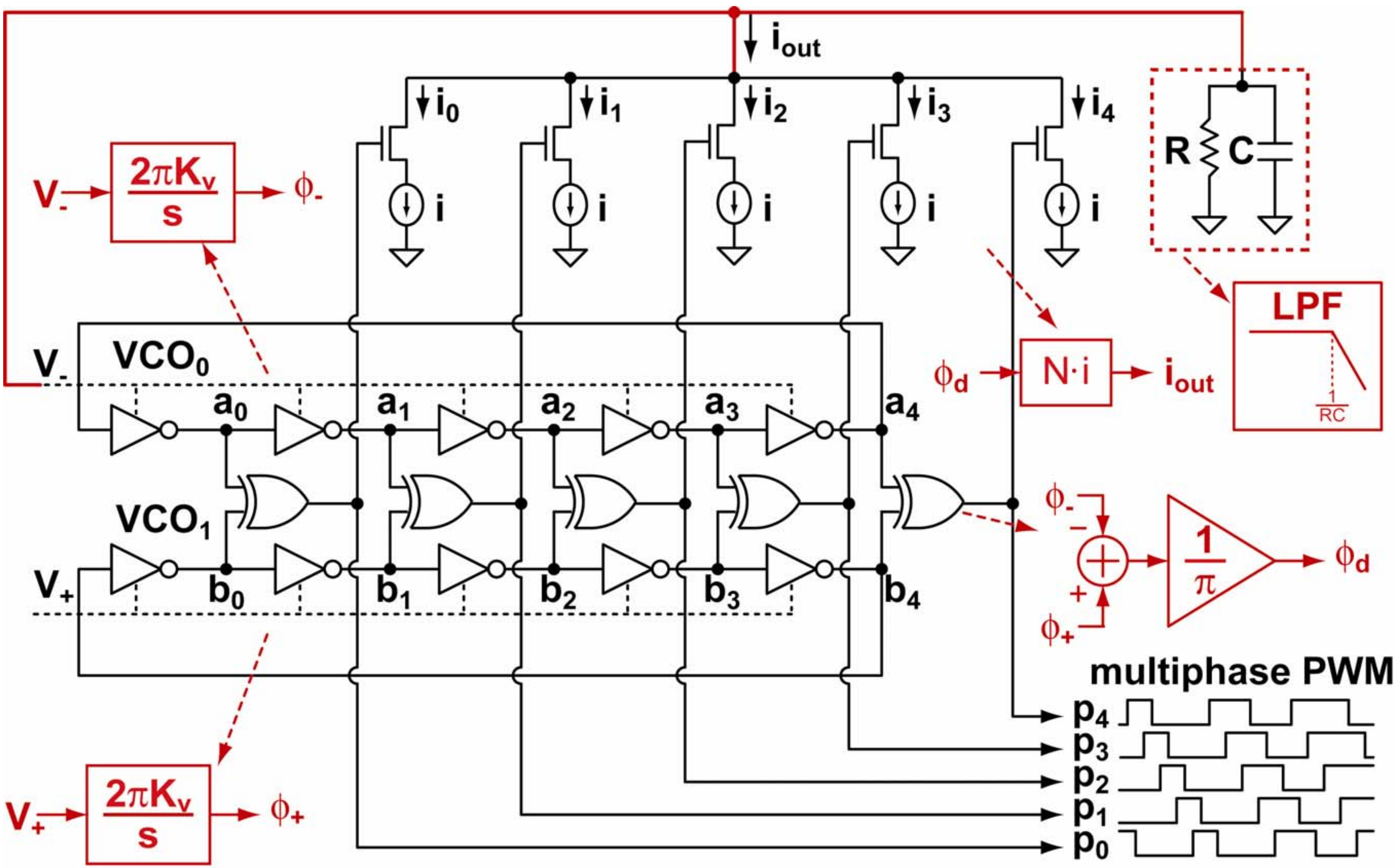
# *Voltage-controlled delay cell*



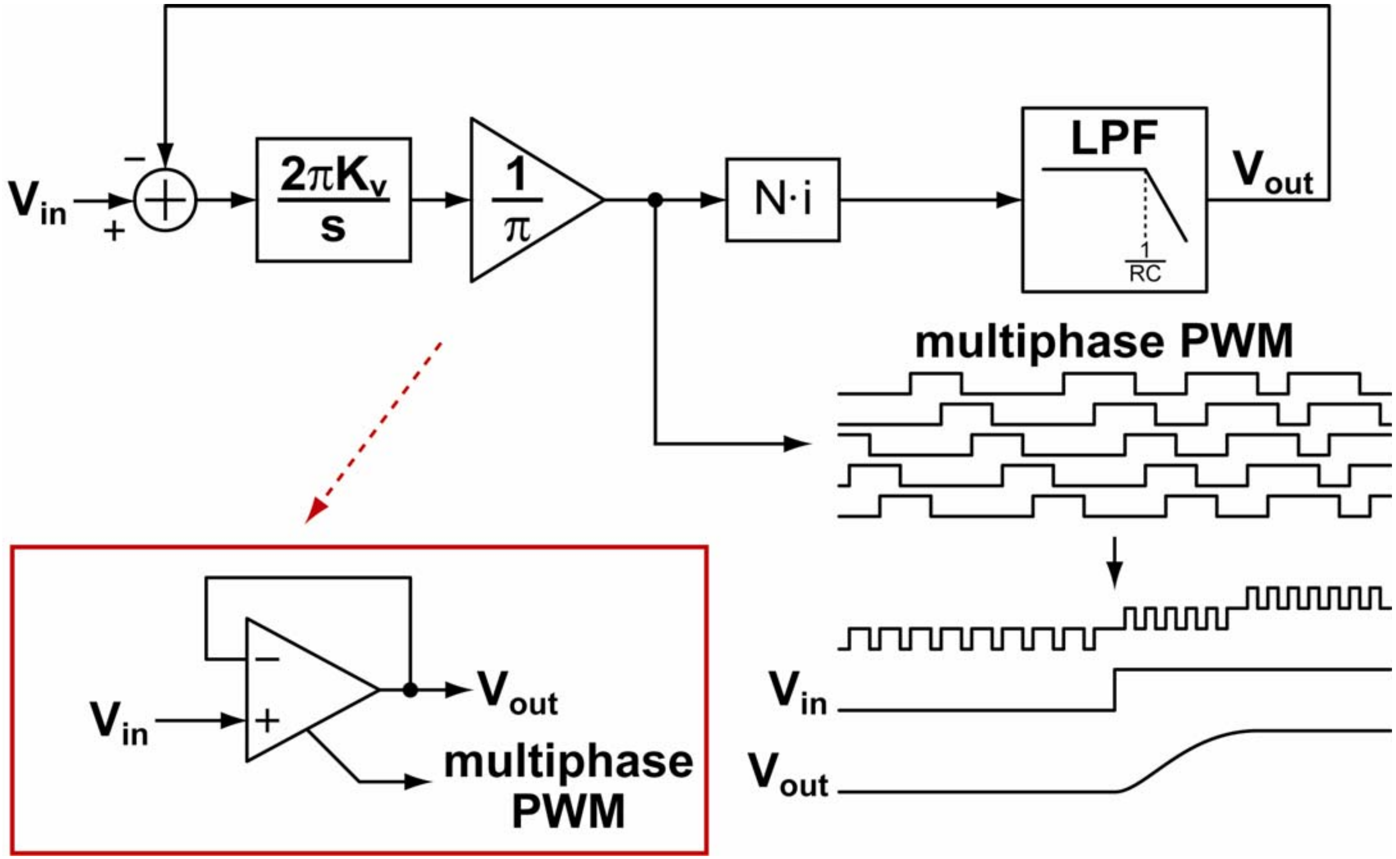
# Combine the Outputs using Switched Current Sources



# Add Feedback and a Simple Filter

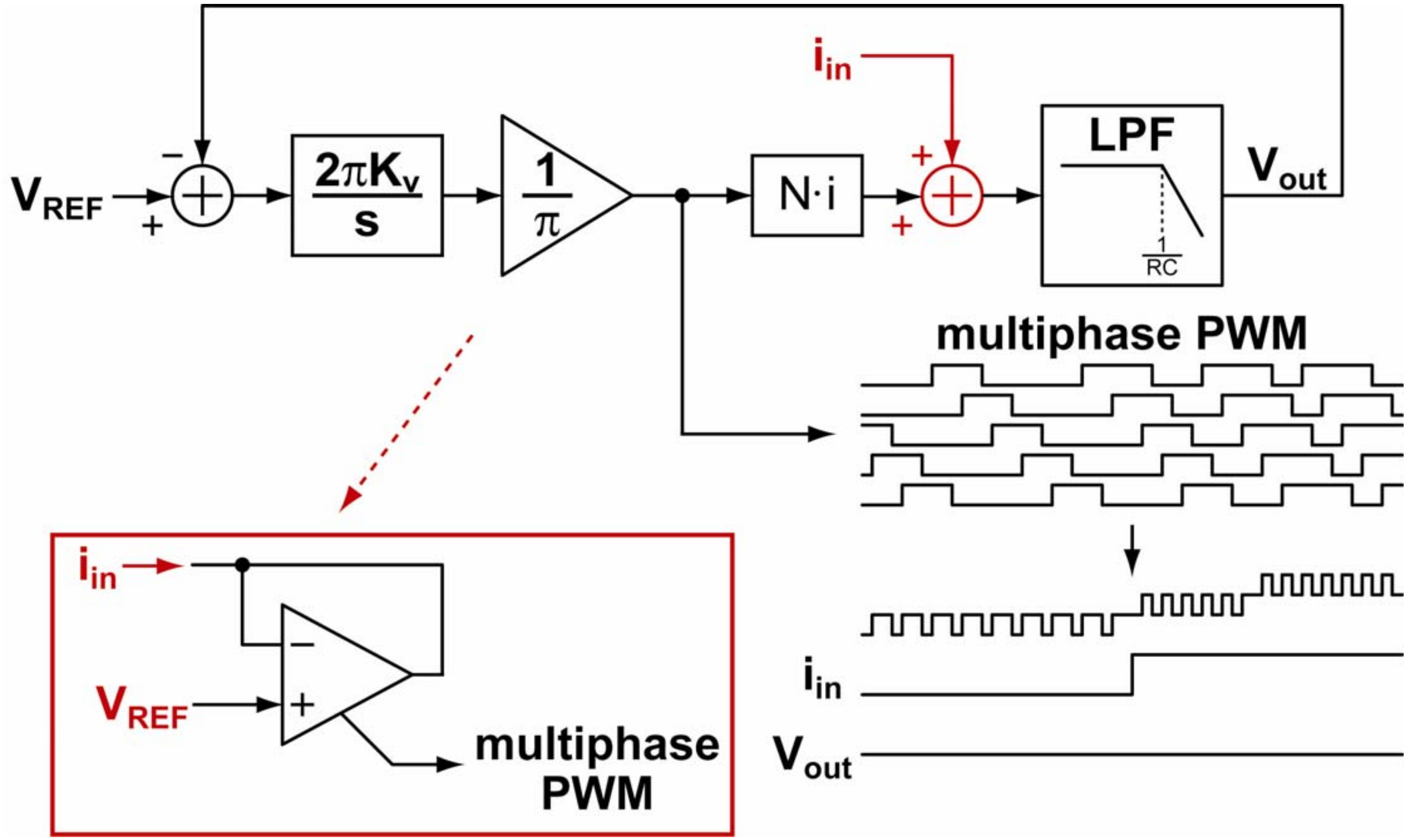


# Overall Model of the Multi-Phase PWM Generator



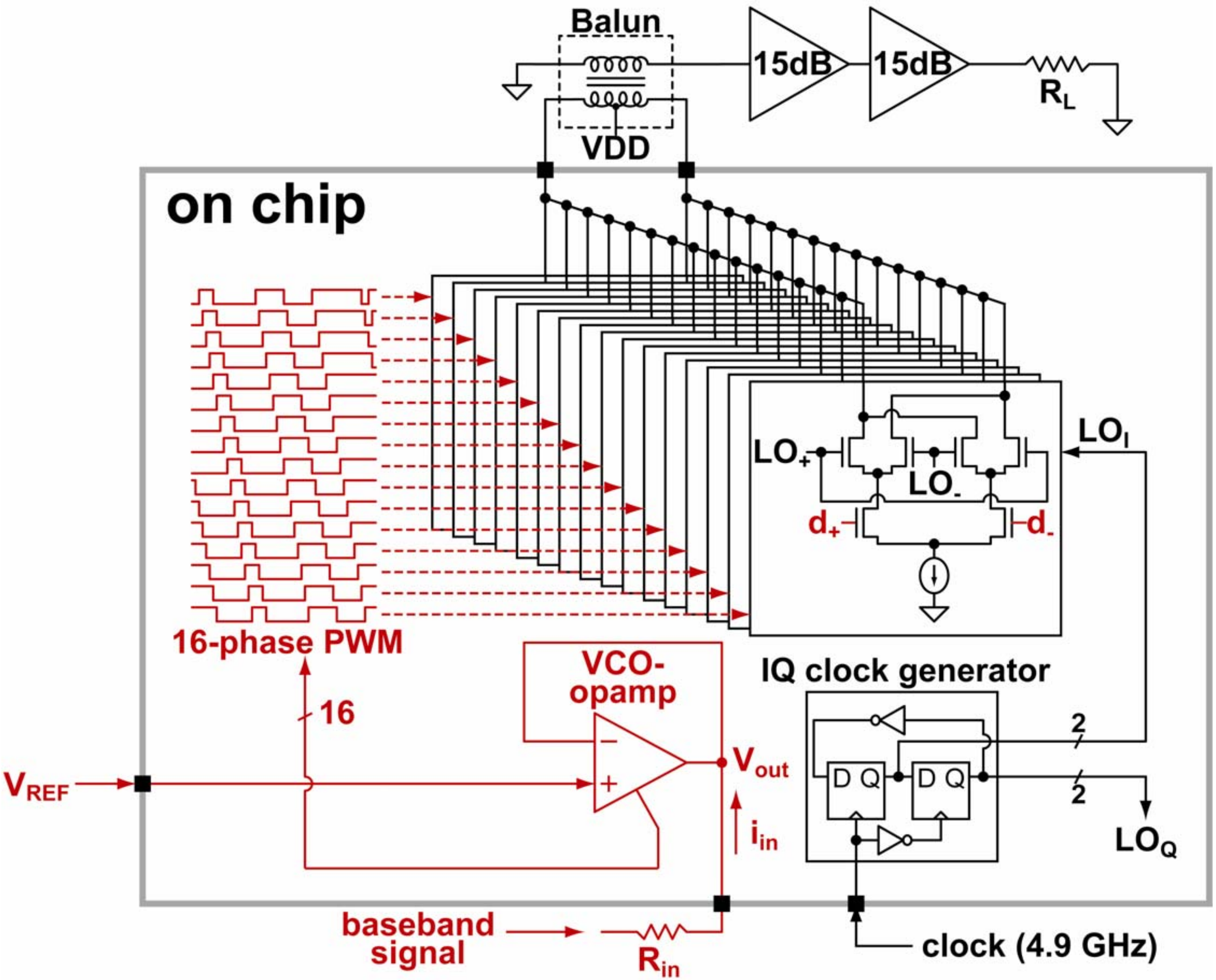

- The proposed negative feedback system is similar to opamp
  - Dominant pole at DC, and the second pole at 1/RC
  - We can consider this structure a *VCO-based opamp*

# *Improve Performance with a Current Input*

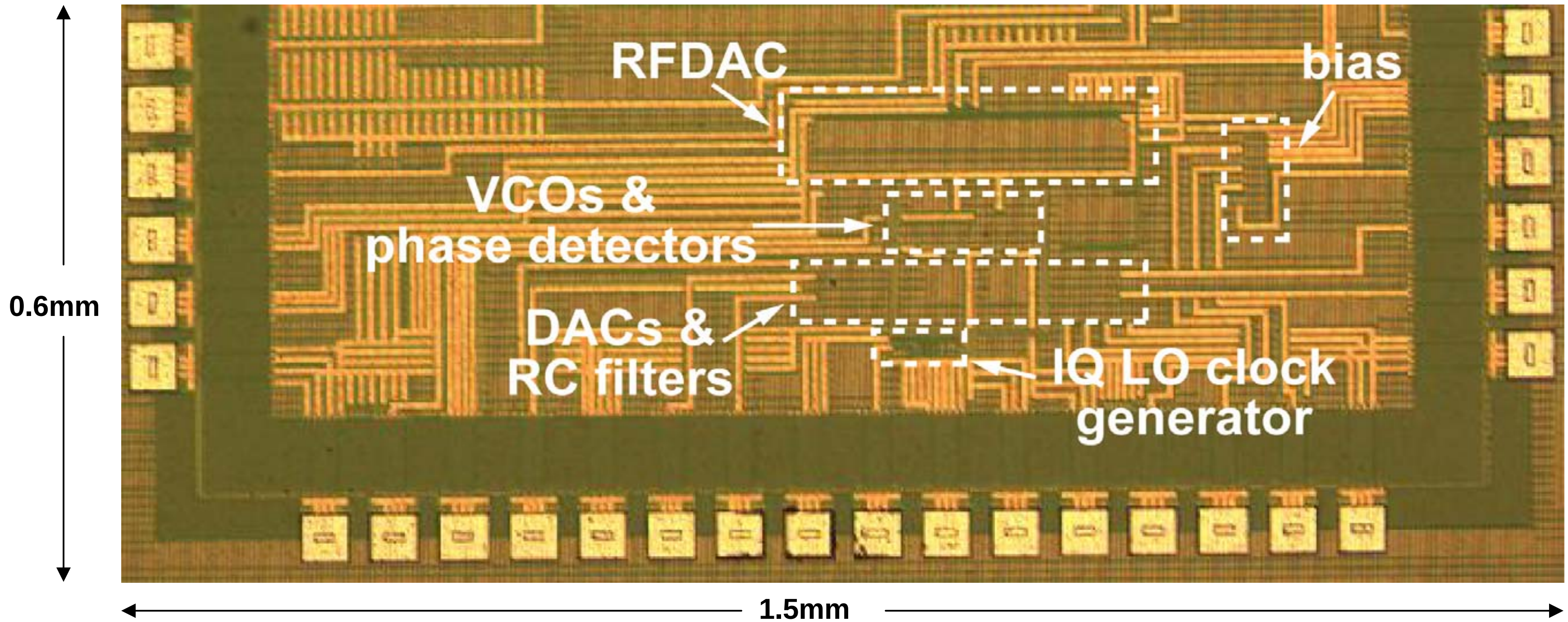



- Input voltage set to $V_{REF}$
  - The feedback loop maintains the other VCO input at $V_{REF}$
  - Allows better control of VCO frequency and $K_V$

# Proposed Multi-Phase PWM RF modulator

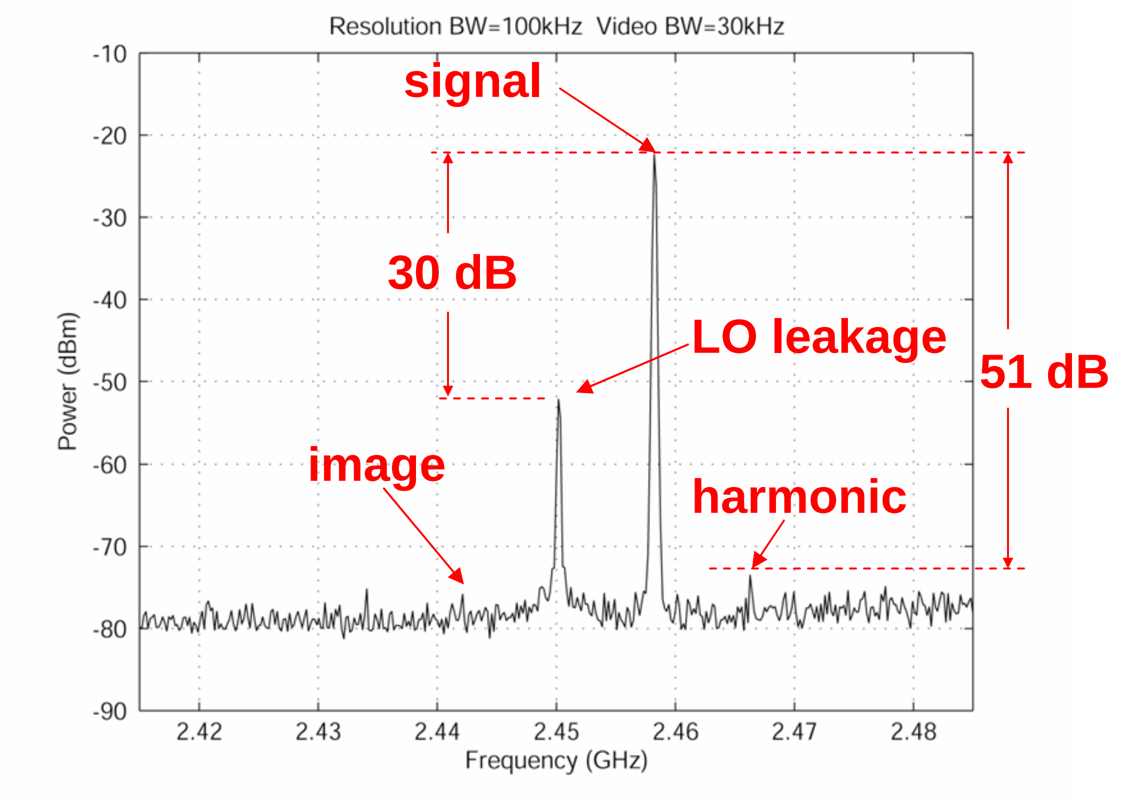


# *Die Photograph*




- 45nm CMOS process
- Total active area : 0.126 mm$^2$
- Supply voltage
  - RFDAC: 2.5V, IQ LO clock generator: 1.2V, others: 1.1V
- Total current consumption : 45.1mA
  - RFDAC :2.2mA, IQ LO clock generator: 16.6mA, others: 26.3mA

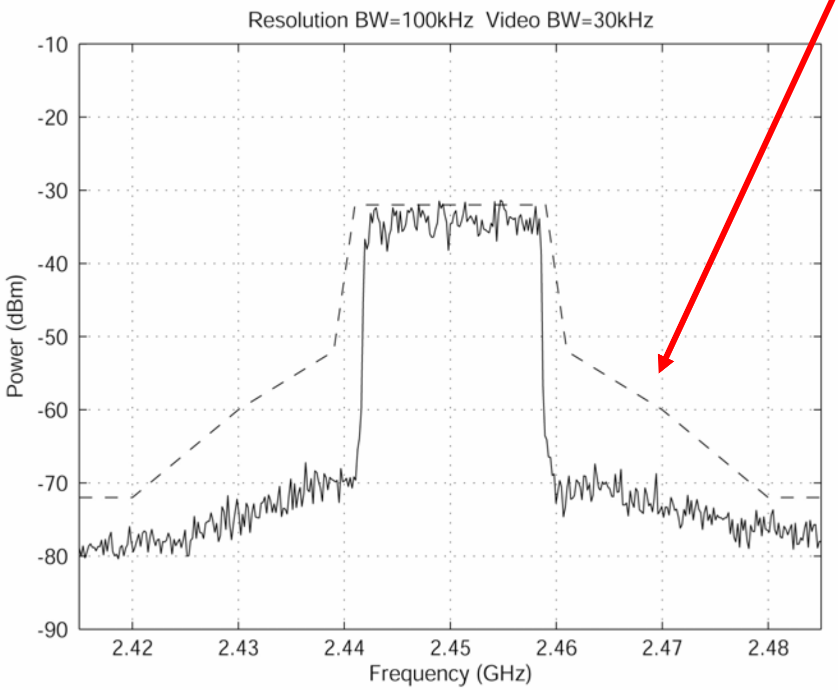
# *Measured Spectrum with 8 MHz Sine Wave Input*



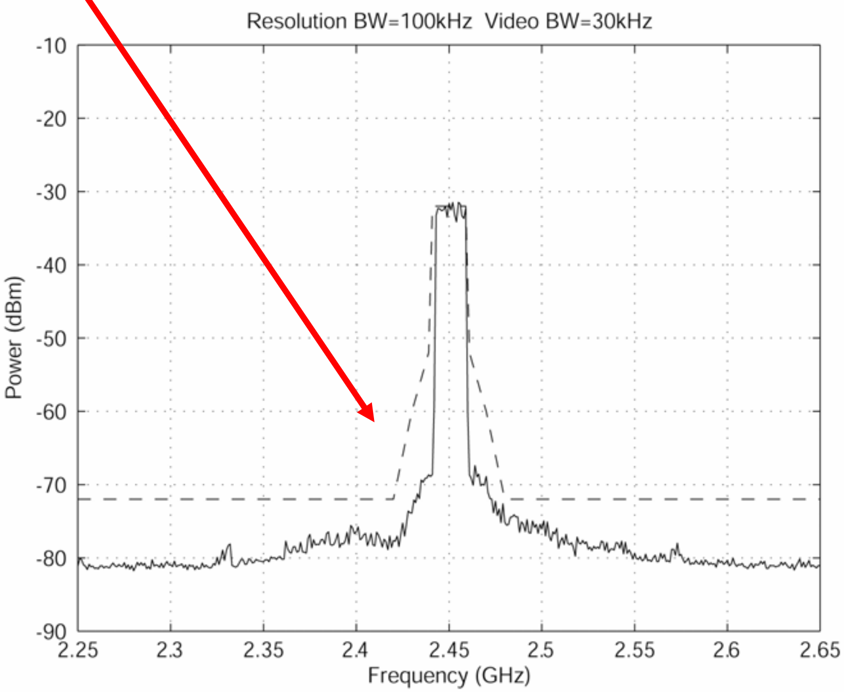

- **LO frequency is 2.45 GHz**
- **IQ gain and phase mismatches are compensated by pre-distortion of the IQ baseband signals**

# *Measured spectrum with a 20 MHz OFDM signal*

**802.11g spectral mask**

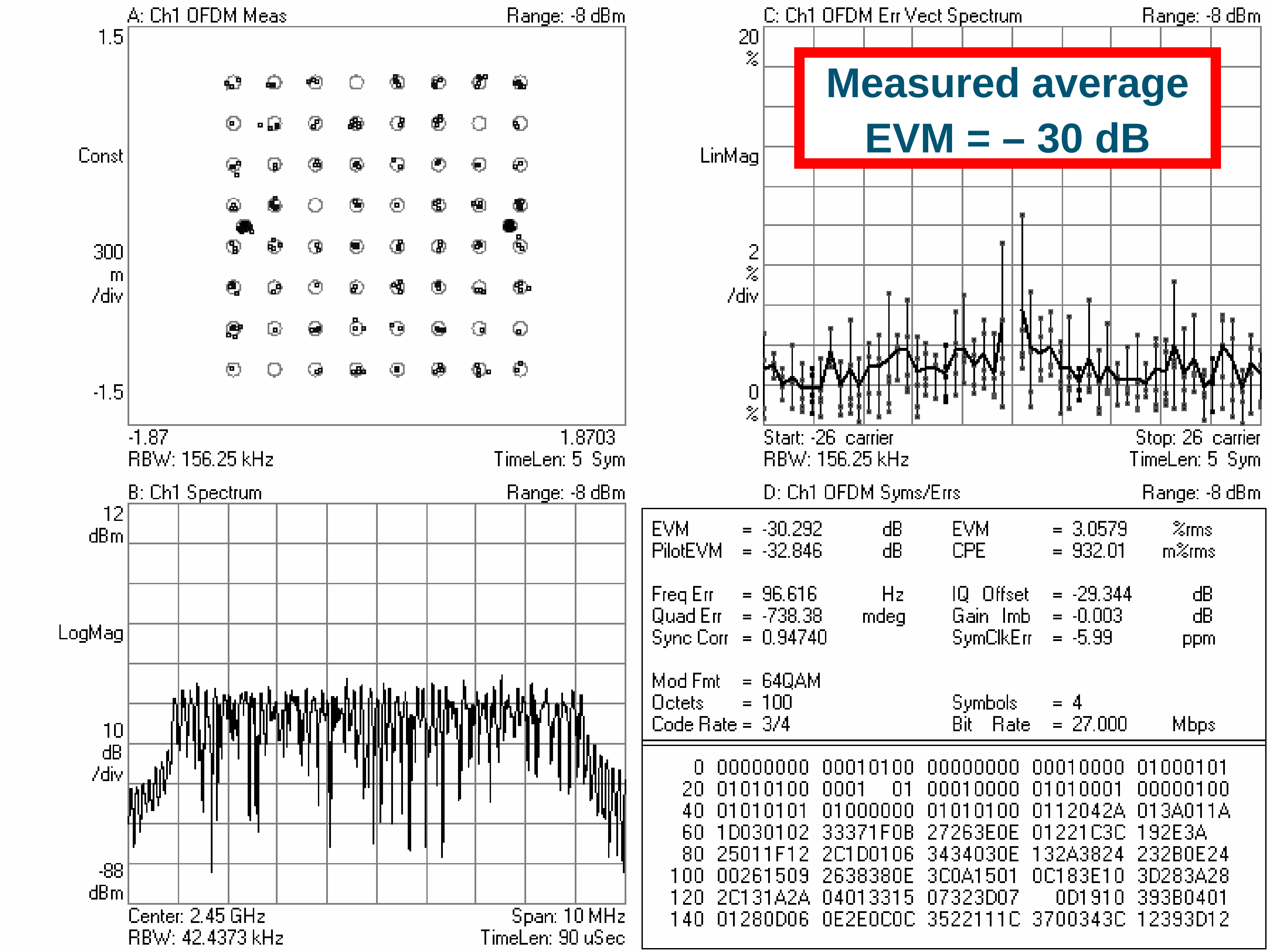



**70 MHz span**



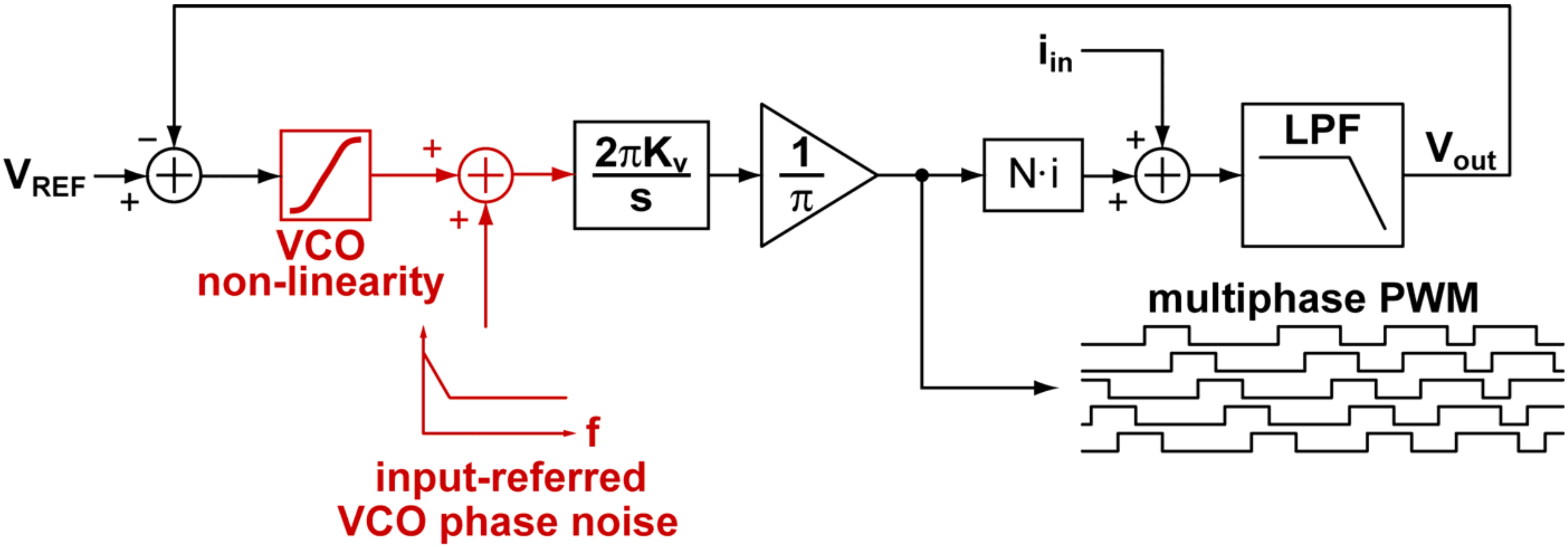

**400 MHz span**

# *Measured EVM with 10-MHz 64 QAM OFDM (802.11a)*




- **1/f noise degrades the EVM near the carrier frequency**

# *Key Issues for Improving Performance*




- VCO non-linearity causes harmonic distortion
  - More difficult for closed loop dynamics to suppress the VCO non-linearity for a wide bandwidth input signal
- VCO phase noise lowers the inband SNR
  - Lower offset frequencies especially impacted

# *Summary*

- ***Multiphase* PWM RF modulator using a VCO-based opamp was presented**
  - **Several advantages over single-phase PWM**
    - Higher ripple frequency
    - Resulting multi-level signal improves dynamic range (and therefore improves SNR)

- **The prototype chip was fabricated in 45nm CMOS**
  - **Satisfies the 802.11g WLAN spectral mask**
  - **Achieves an average measured EVM of –30 dB for 10-MHz, 64 QAM OFDM at 2.4 GHz**