High Linearity Oscillator Architectures Band-Pass Based

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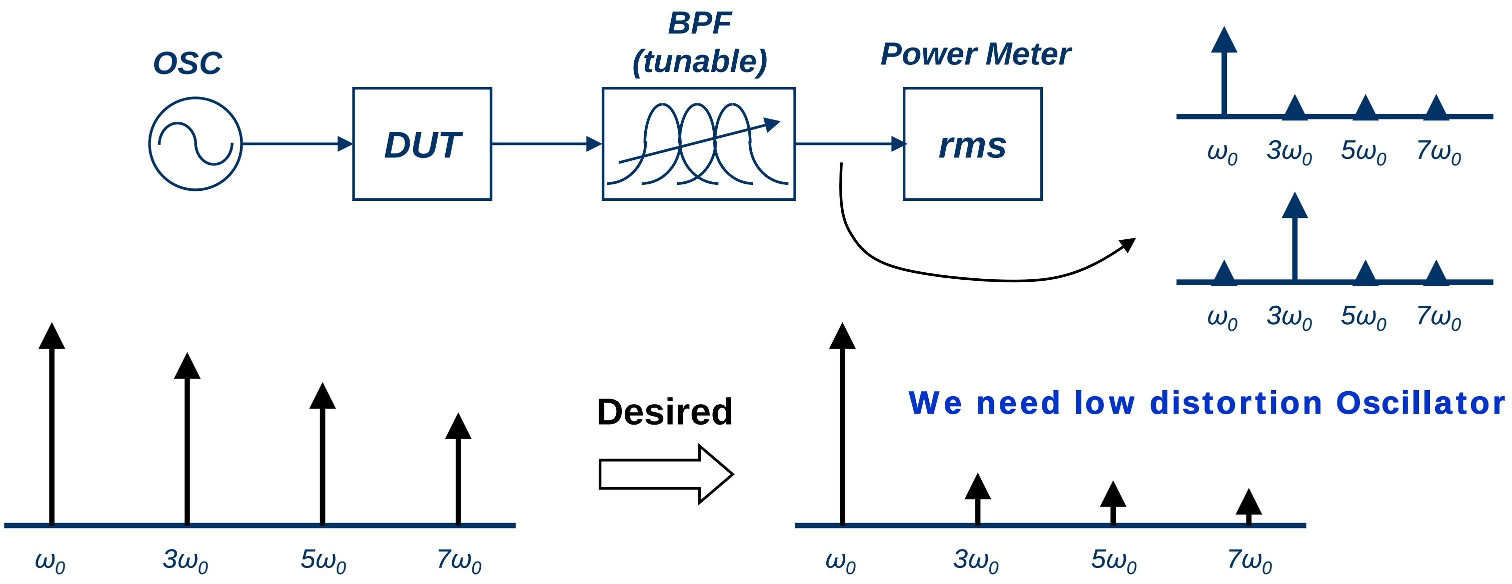
Outline of Presentation

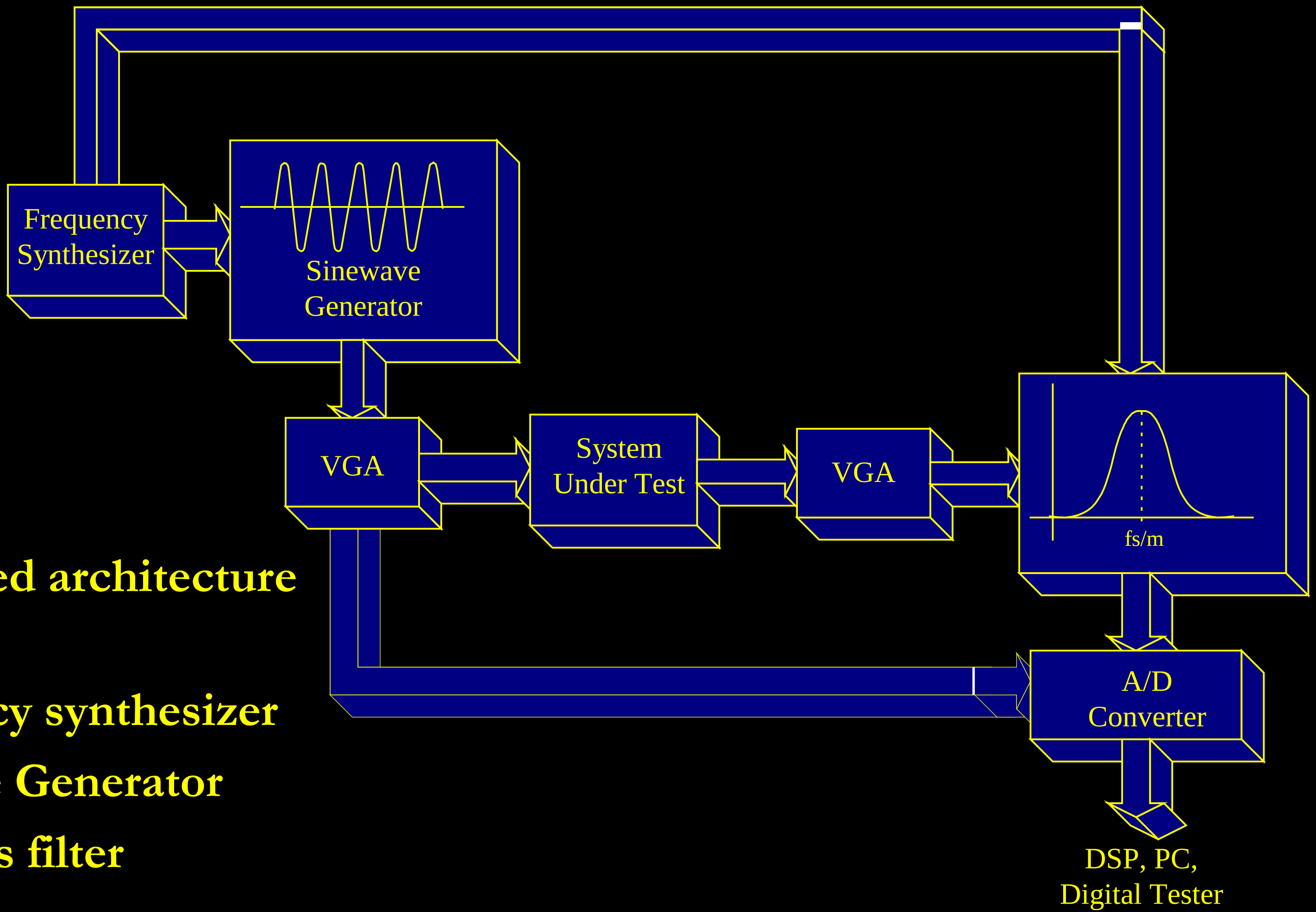
- Oscillator Background and General Design Consideration.
- Non-Linear Shaping Oscillator with Enhanced Linearity.
  - Continuous-time implementation.
  - Discrete-time implementation.
  - Time-Mode-Based Tunable Oscillator.
- Comparison and Conclusions

Oscillator Applications

- Built-in self testing (BIST)
  - Sinusoidal oscillator
  - Low total harmonic distortion (THD) is desired
  - Popular structure : BPF-based oscillator



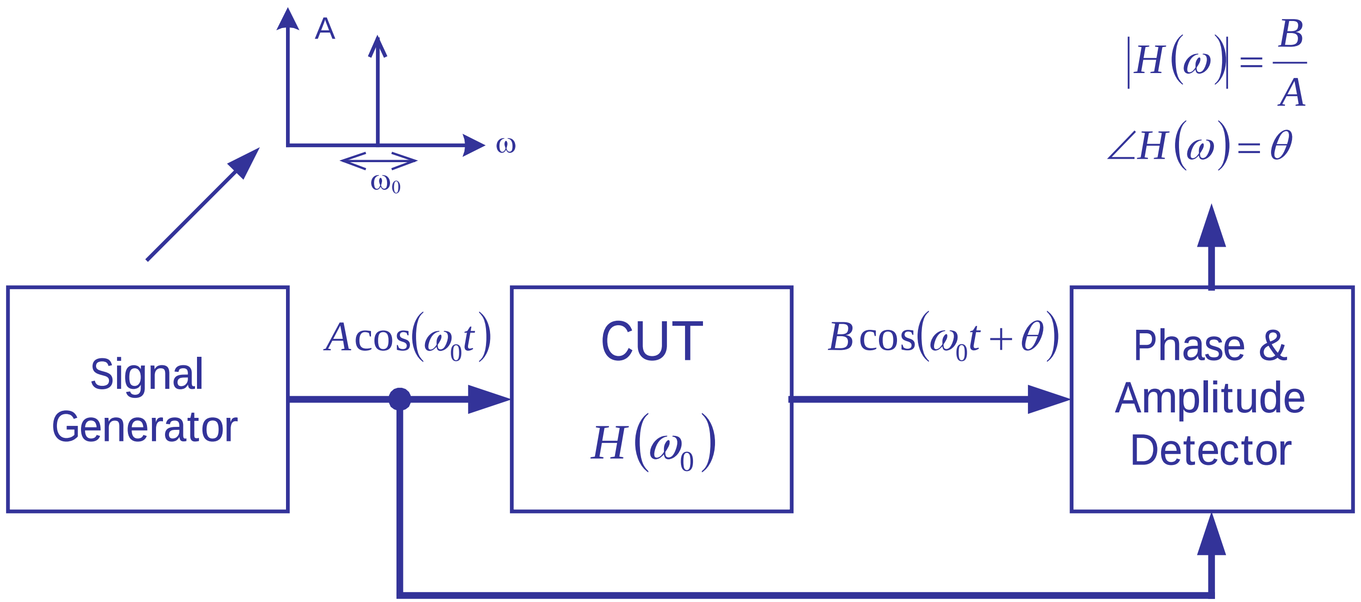
On-Chip Spectrum Analyzer



The proposed architecture contains:

- **Frequency synthesizer**
- **Sinewave Generator**
- **Bandpass filter**
- **VGA**

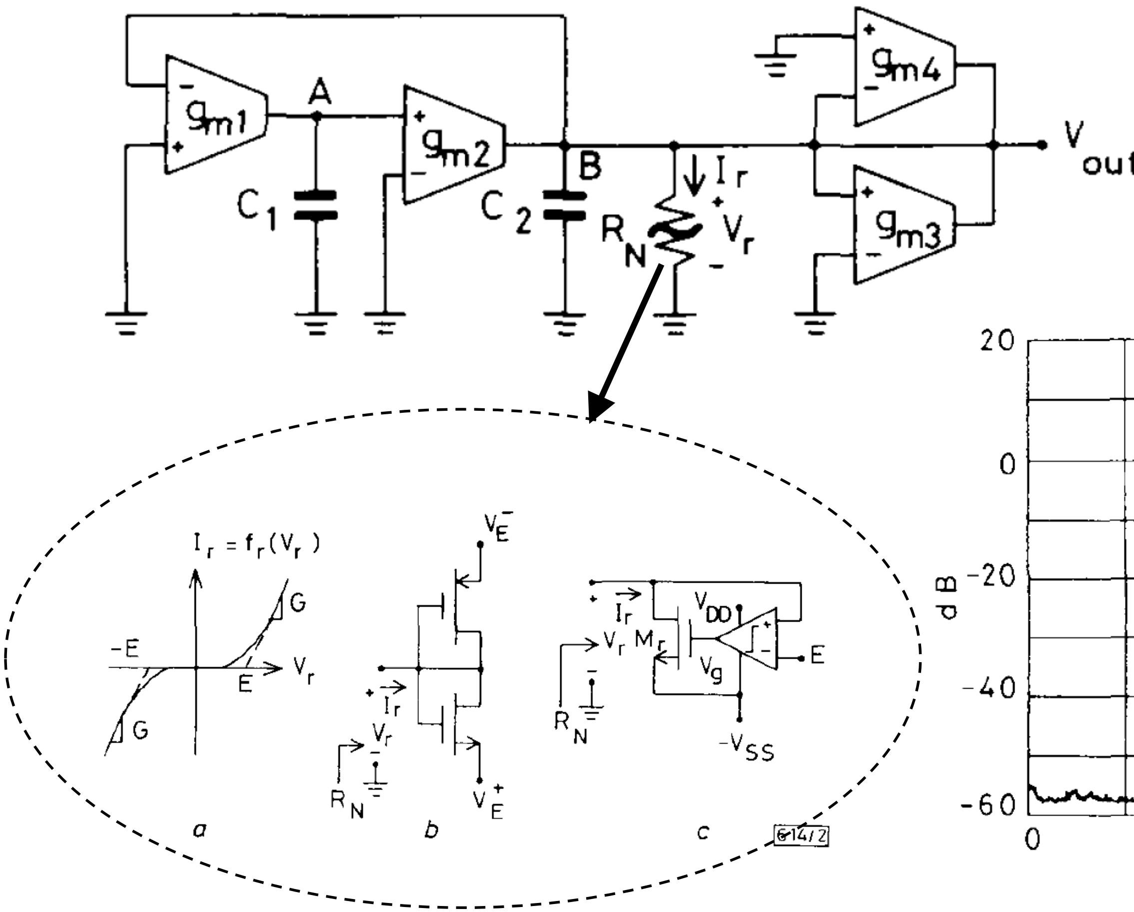
TRANSFER FUNCTION CHARACTERIZATION

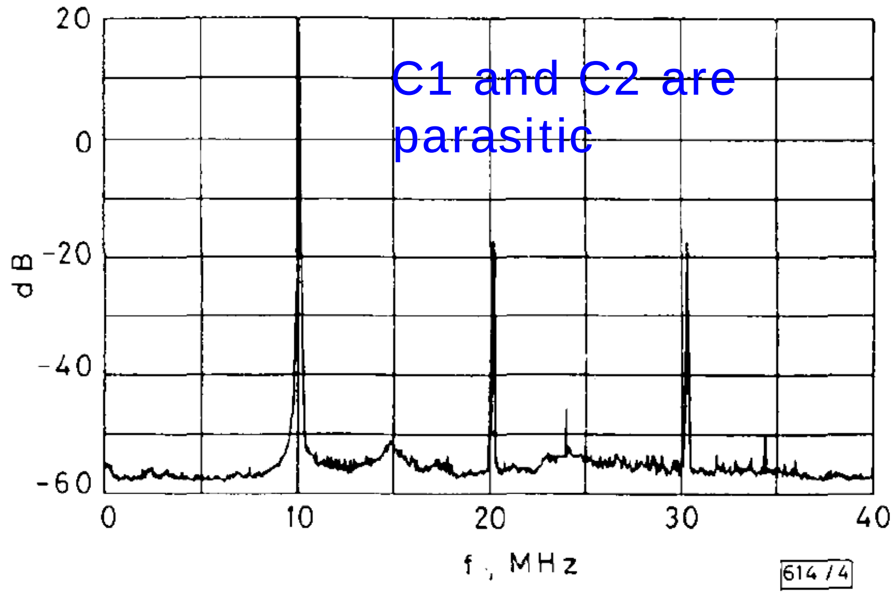


At a given frequency, the transfer function of a circuit under test (CUT) can be obtained by comparing the amplitude and phase of the signals at the input and output.

Our first integrated 10MHz CMOS OTA-C Voltage-Controlled Quadrature Oscillator in 1989

- 3-10.34 MHz
- THD: 0.2-1.87%
  (-54dB to -34.5dB)
- Vpp: 0.1-1V





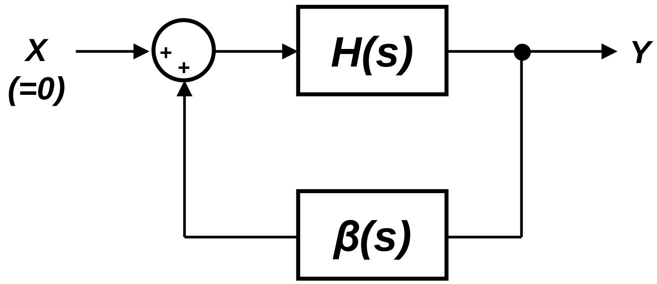
C1 and C2 are parasitic

B. Linares-Barranco, A. Rodriquez-Vazquez, E. Sanchez-Sinencio, J.L. Huertas, "10 MHz CMOS OTA-C voltage-controlled quadrature oscillator," Electronics Letters , vol.25, no.12, pp.765-767, 8 June 1989

Oscillator Background and

General Design Considerations

Barkhausen's Condition



- ❑ Feedback system is unstable and will oscillate if

  - Total gain through the loop is 1

$$\left|H(s)\beta(s)\right| = 1$$

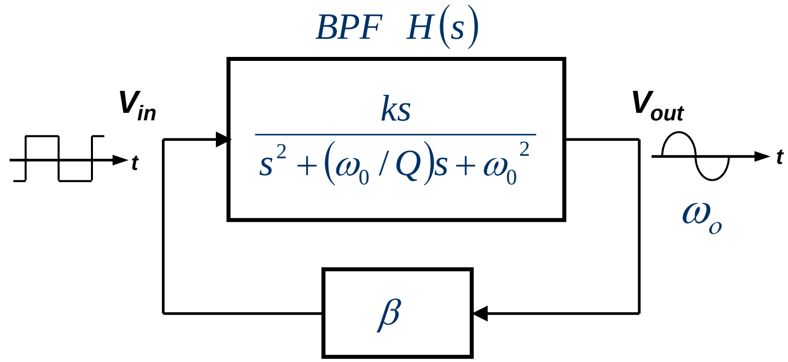
  - Total phase shift around loop is 2πn (n = 0, 1, 2, …)

$$\angle H(s)\beta(s) = 2\pi n,\ n \in 0,1,2,....$$

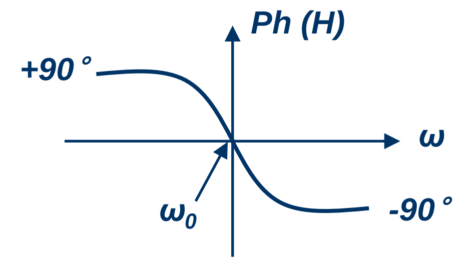
- ❑ Closed loop equation

$$\frac{H(s)}{1 - H(s)\beta(s)}$$

A Band Pass Filter plus a Positive Feedback yields an Oscillator

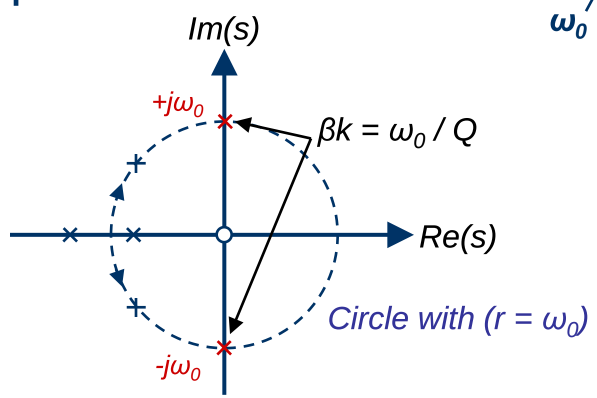


- Assume H(s) is a second-order BPF and β(s) has a linear gain β
- **Barkhausen condition**
  - Phase condition is satisfied due to BPF
  - Gain condition from closed loop equation:



$$\left|\beta H(j\omega_0)\right| = \left|\frac{j\beta k\omega_0}{j\omega_0^{\,2}/Q}\right| = 1$$

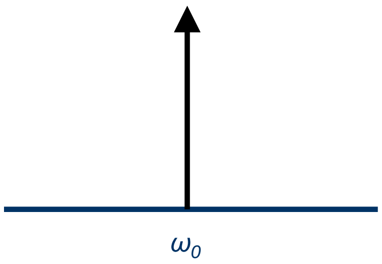
$$\Rightarrow \quad \beta k = \omega_0 / Q$$



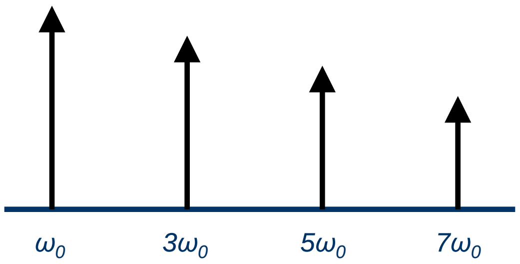
Oscillator Performance

- General consideration
  - Amplitude
  - Frequency accuracy
  - Power consumption, Silicon area

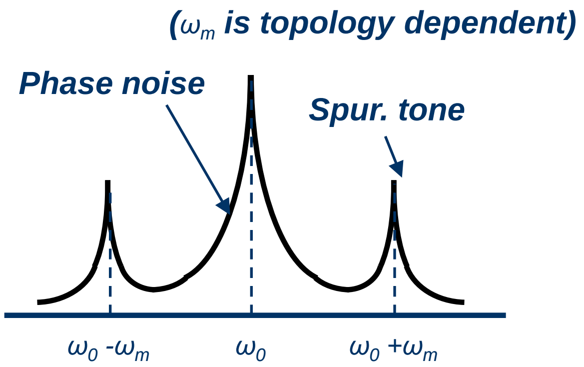
- Spectral purity



Ideal



Non-Ideal contains harmonics



Phase noise and Spur

Non-Linear Shaping Oscillator with Enhanced Linearity

(10 MHz Sinusoidal Oscillator)

- ✓ **Motivation**

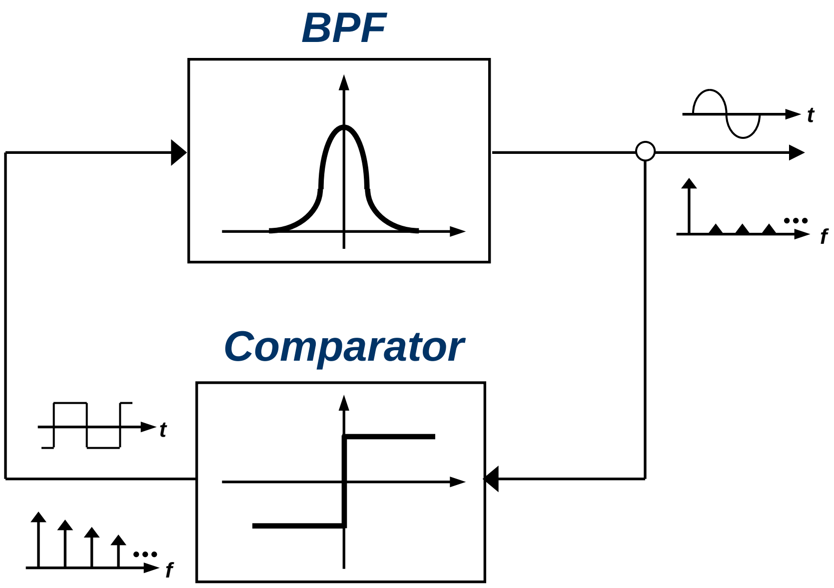
  Improve linearity with low-cost solution

- ✓ **Proposed Solution**

  Harmonic rejection with multi-level square wave technique

Conventional BPF-based Oscillator

- Oscillation frequency is set by BPF
- Oscillation is guaranteed by high gain of comparator
- Linearity is heavily dependent on Q-factor of BPF
- Requires high Q-factor BPF

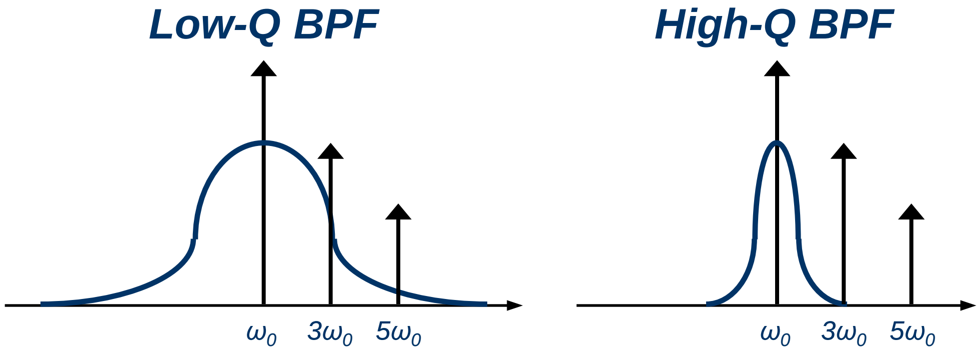


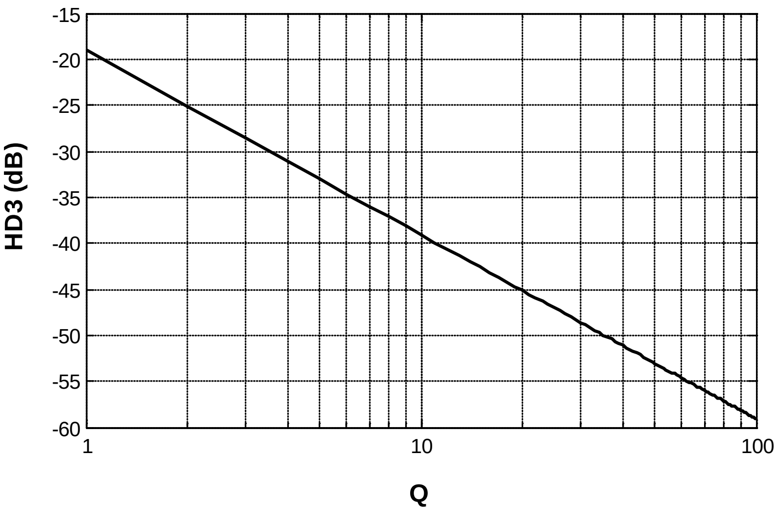
BPF-based Oscillator

- Input of BPF is roughly a square wave
- THD is dominated by lower order harmonics
- Requires very high Q-factor for low distortion

  (i.e. Q = 35 is required for HD3 = -50 dB)

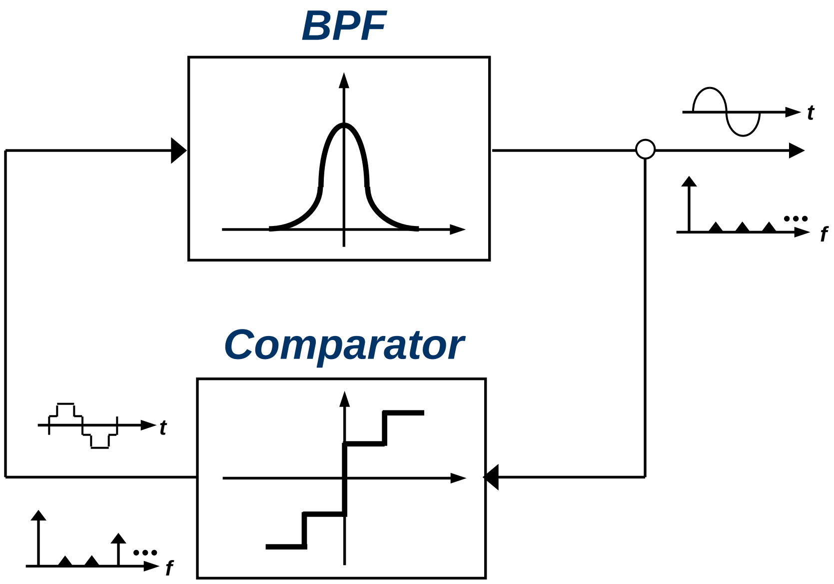
$$HD_n \approx \frac{1}{n^2 Q}$$





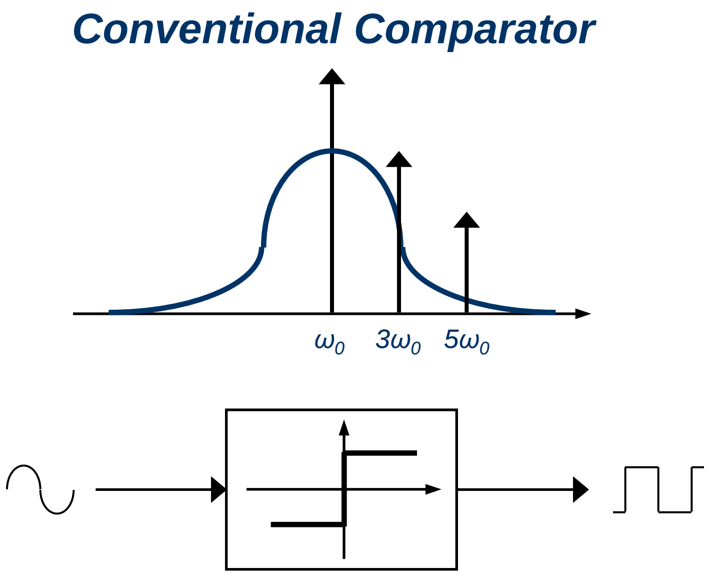
How can the linearity of BPF-based Oscillator be improved ?

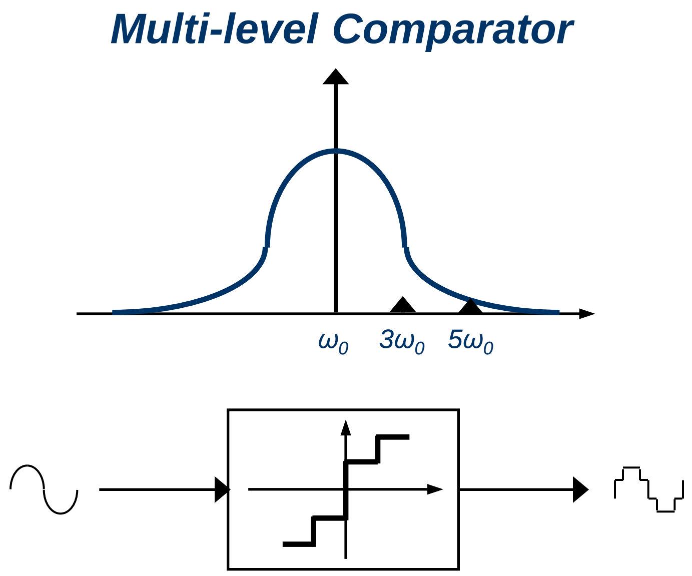
- ❑ Use Multilevel comparator yielding lower-order harmonic components
- ❑ BPF Q-factor requirement can be relaxed



Proposed BPF-based Oscillator Using multi-level comparator

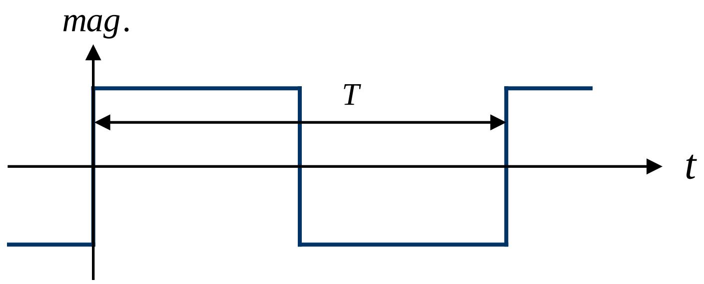
- Lower-order harmonics are rejected by multilevel comparator
- High linearity can be achieved without high-Q BPF



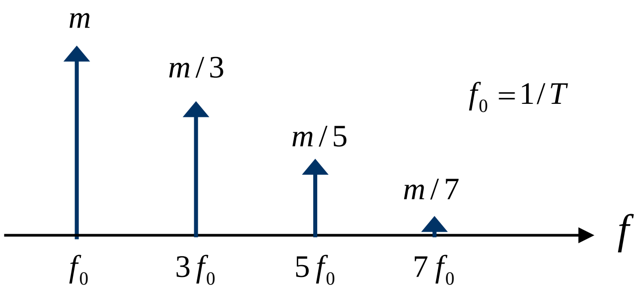


Square Wave Analysis

- Common signal source
- Easy to implement
- Full family of odd harmonics
- No even harmonics due to symmetric property
- Most significant harmonics : 3rd and 5th order



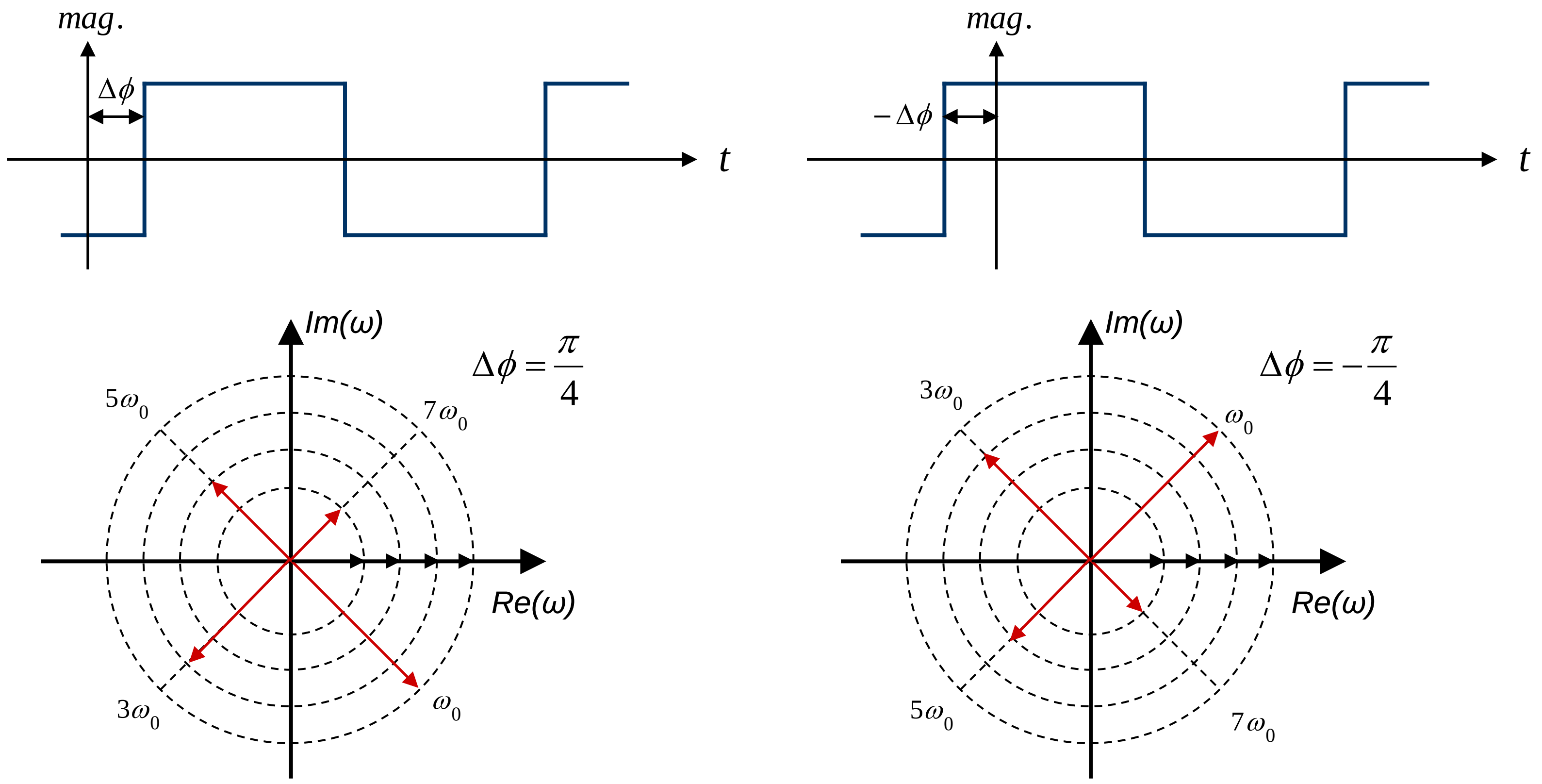
Time domain



Frequency domain

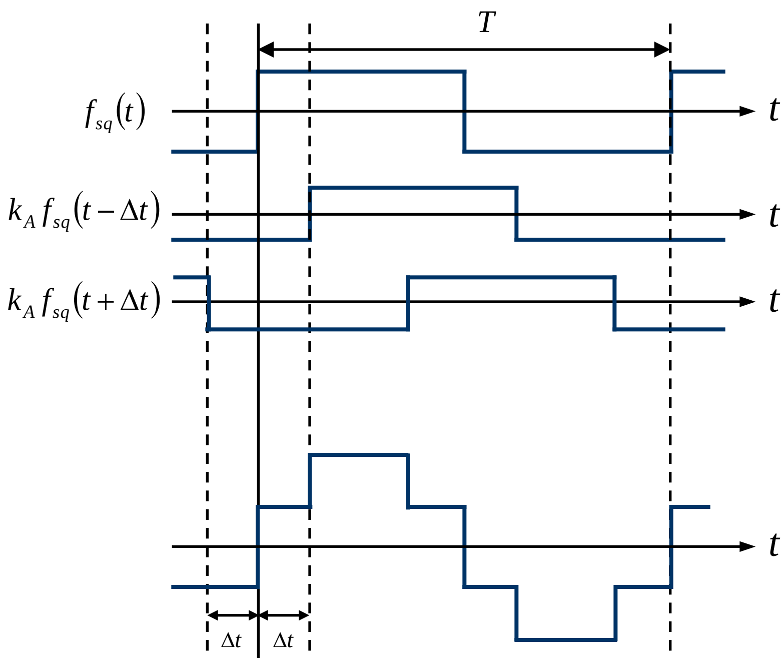
Shifted Square Wave

- Shift in time-domain → Phase deviation in frequency domain
- Different phase-shift for each harmonics



Multi-Level Square Wave

- Multiple time-shifted with amplification square waves



$$F_{sq}(\omega)$$

$$k_A e^{-j\Delta t\omega} F_{sq}(\omega)$$

$$k_A e^{+j\Delta t\omega} F_{sq}(\omega)$$

$$F(\omega) = \left(1 + 2k_A \cos(\Delta t\omega)\right) F_{sq}(\omega)$$
$$= H(\omega) F_{sq}(\omega)$$

$$f(t) = f_{sq}(t) + k_A f_{sq}(t - \Delta t) + k_A f_{sq}(t + \Delta t)$$

$$H(n\omega_0) = 1 + 2k_A \cos(\Delta t n\omega_0)$$

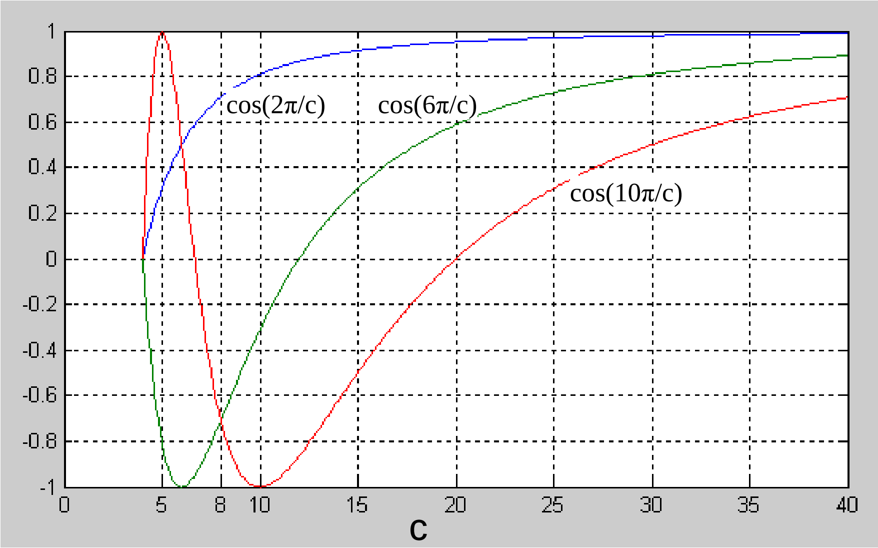
How to Determine Values for $H(3\omega_o)=H(5\omega_o)=0$?

- Multiple time-shifted with amplification square waves
  - Assuming Δt = T/c and evaluating $H(n\omega_0)$ at n = 1, 3, 5

$$H(3\omega_0)=1+2k_A\cos(6\pi/c) \qquad H(5\omega_0)=1+2k_A\cos(10\pi/c)$$

  - If we want $H(3\omega_0) = H(5\omega_0) = 0$,

    then $\cos(6\pi/c) = \cos(10\pi/c) = -1/(2k_A)$



- Optimal Values

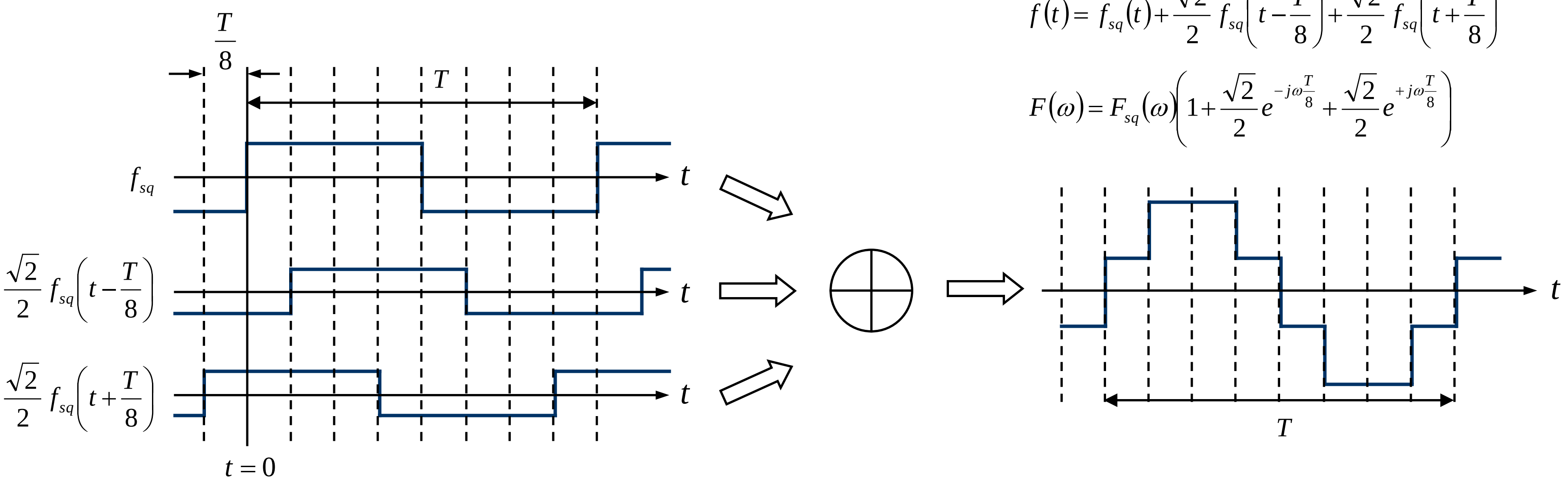
$$c=8$$

$$k_A=\frac{-1}{2\cos(3\pi/4)}=\frac{\sqrt{2}}{2}$$

Sum of Shifted Square Waves without 3rd and 5th Harmonics

$$f(t) = f_{sq}(t) + \frac{\sqrt{2}}{2} f_{sq}\left(t - \frac{T}{8}\right) + \frac{\sqrt{2}}{2} f_{sq}\left(t + \frac{T}{8}\right)$$

$$F(\omega) = F_{sq}(\omega)\left(1 + \frac{\sqrt{2}}{2} e^{-j\omega\frac{T}{8}} + \frac{\sqrt{2}}{2} e^{+j\omega\frac{T}{8}}\right)$$



$$F(\omega_0) = F_{sq}(\omega_0)\left(1 + \sqrt{2}\cos\left(\frac{\pi}{4}\right)\right) = 2F_{sq}(\omega_0)$$

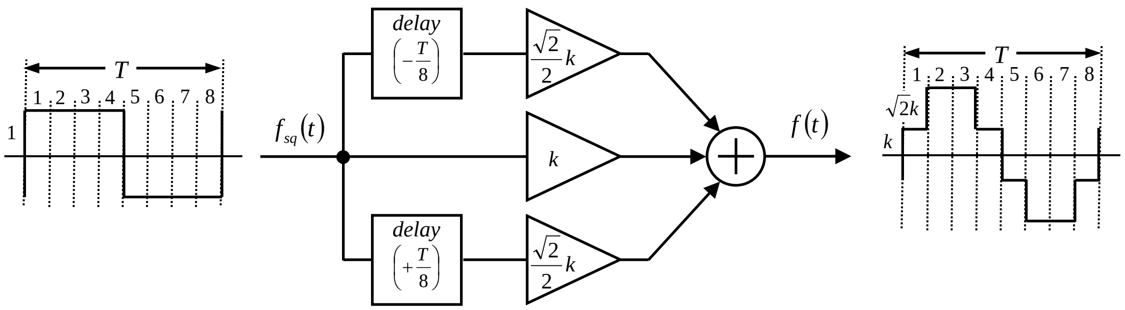
$$F(3\omega_0) = F_{sq}(3\omega_0)\left(1 + \sqrt{2}\cos\left(\frac{3\pi}{4}\right)\right) = 0$$

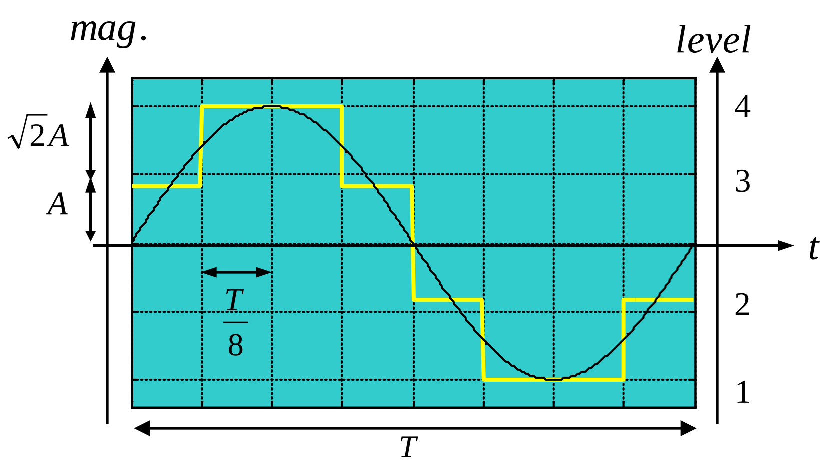
$$F(5\omega_0) = F_{sq}(5\omega_0)\left(1 + \sqrt{2}\cos\left(\frac{5\pi}{4}\right)\right) = 0$$

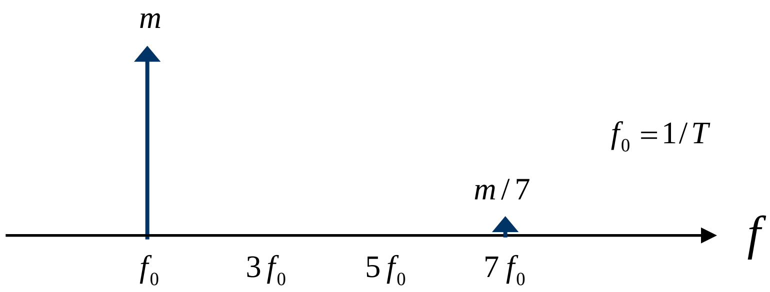
$$F(7\omega_0) = F_{sq}(7\omega_0)\left(1 + \sqrt{2}\cos\left(\frac{7\pi}{4}\right)\right) = 2F_{sq}(7\omega_0)$$

How to Implement the Sum of Shifted Signals?

- Optimized multi-level square wave $$f(t) = f_{sq}(t) + \frac{\sqrt{2}}{2} f_{sq}\left(t - \frac{T}{8}\right) + \frac{\sqrt{2}}{2} f_{sq}\left(t + \frac{T}{8}\right)$$
  - Selectively rejects 3rd and 5th harmonics







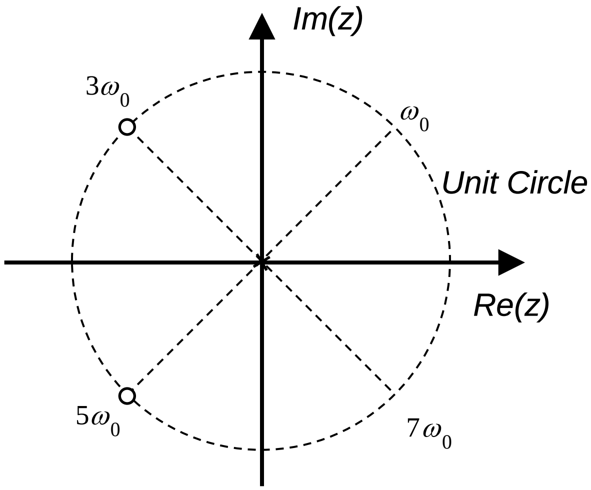
Implementation in the Z-Domain

- Recalling $H(n\omega_0) = e^{-jn\Delta\phi}$ and $\Delta\phi = 2\pi / c \;\Rightarrow\; H(c\omega_0) = e^{-j2\pi}$
- Setting

$$z = e^{j\Delta t\omega} = e^{j\Delta\phi\omega/\omega_0} = e^{j2\pi\omega/(c\omega_0)} \qquad \frac{\Im\{f_{sq}(t+n\Delta t)\}}{\Im\{f_{sq}(t)\}} = e^{jn\Delta t\omega} = z^n$$

- Consider previous case (c = 8, Δt = T/8)

  - If we want H(*3ω$_0$*) = H(*5ω$_0$*) = 0,



$$H(z) = \frac{\left(z - e^{+j3\pi/4}\right)\left(z - e^{-j3\pi/4}\right)}{z} = z + \sqrt{2} + z^{-1}$$

$$f(t) = f_{sq}(t - T/8) + \sqrt{2}\, f_{sq}(t) + f_{sq}(t + T/8)$$

$$= \sqrt{2}\left[\frac{\sqrt{2}}{2} f_{sq}(t - T/8) + f_{sq}(t) + \frac{\sqrt{2}}{2} f_{sq}(t + T/8)\right]$$

Oscillator Design Procedure in the Z-Domain

- Generalized procedure

  - Determine $c = T/\Delta t$

  - 2π corresponds to $c\omega_0$

  - Place conjugate zeros on specific harmonics

  - Place poles at the origin to center delays at zero delay

  - Achieve z-equation

  - Construct time-domain signals

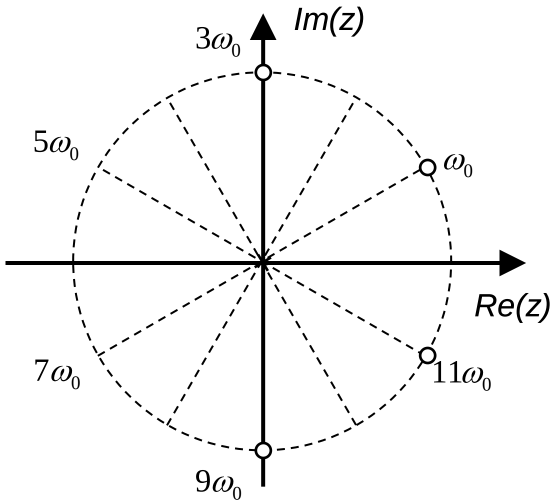
Z-Domain BP Based Oscillator Considerations

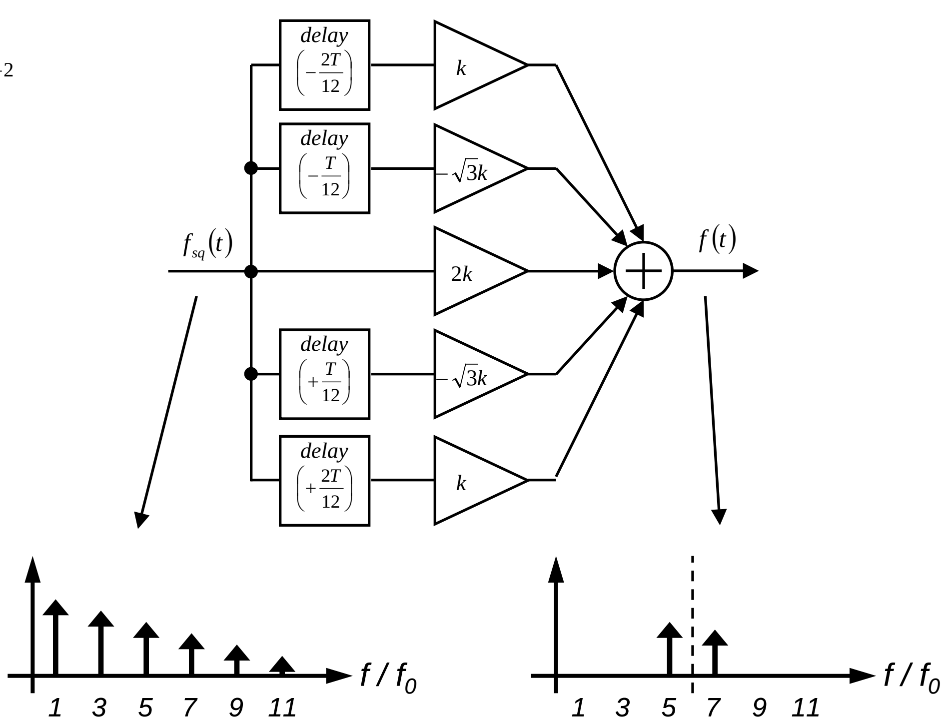
- Example

  - c = 12 and $H(\omega_0) = H(3\omega_0) = H(9\omega_0) = H(11\omega_0) = 0$

$$f(t) = f_{sq}(t - 2T/12) + \sqrt{3} f_{sq}(t - T/12) + 2 f_{sq}(t) + \sqrt{3} f_{sq}(t + T/12) + f_{sq}(t - 2T/12)$$

$$H(z) = \frac{\left(z - e^{+j3\pi/6}\right)\left(z - e^{-j3\pi/6}\right)\left(z - e^{+j\pi/6}\right)\left(z - e^{-j\pi/6}\right)}{z^2}$$
$$= \left(z + z^{-1}\right)\left(z - \sqrt{3} + z^{-1}\right) = z^2 - \sqrt{3}z + 2 - \sqrt{3}z^{-1} + z^{-2}$$





Non-Ideality Considerations in the Z-Domain

- Non-ideal effect

  - Consider the case of c = 8 and H(3ω_0) = H(5ω_0) = 0

  - Recalling $H(n\omega_0) = 1 + k_A \cos(n\Delta\phi), \quad \text{where } k_A = \sqrt{2},\ \Delta\phi = \pi/4$

  - Introduce magnitude error (Δ_m) and phase error (Δ_p)

$$k_A = (1+\Delta_m)\sqrt{2},\ \Delta\phi = (1+\Delta_p)\pi/4$$

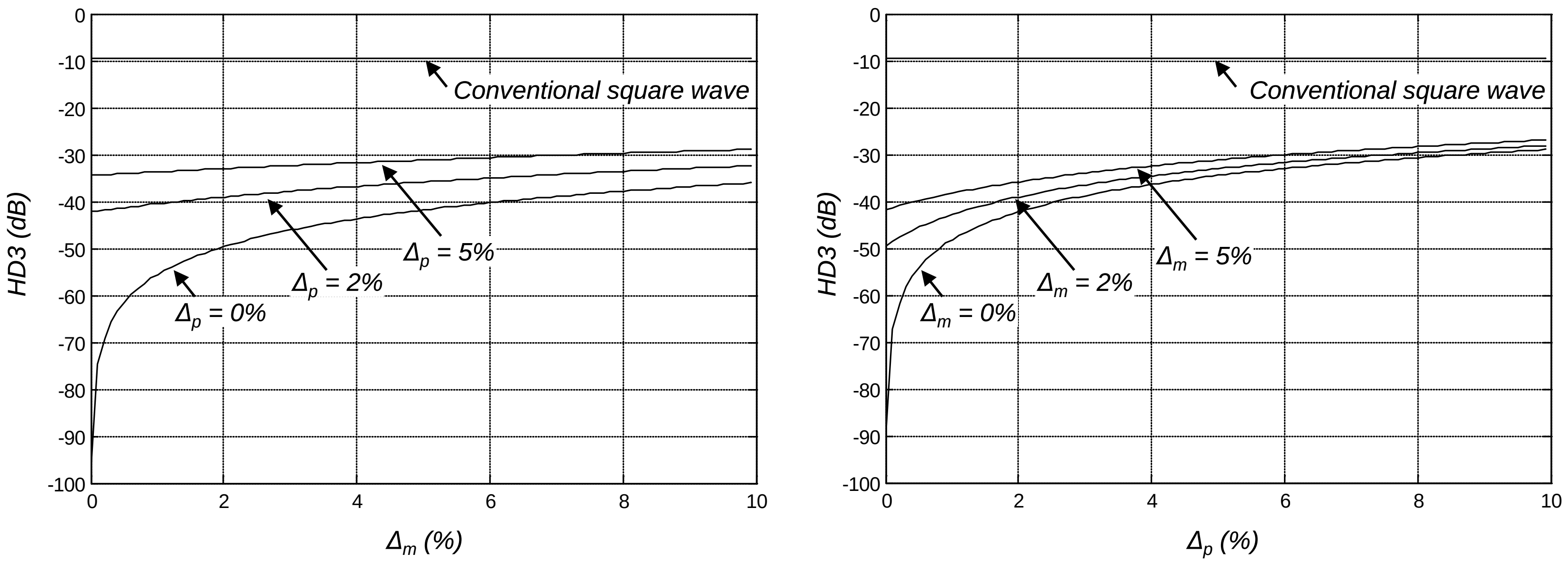
$$H(n\omega_0) = V_a\left\{1 + (1+\Delta_m)\sqrt{2}\cos\left(n(1+\Delta_p)(\pi/4)\right)\right\}$$

  - Evaluating HD3

$$HD3 = \frac{|F(3\omega_0)|}{|F(\omega_0)|} = \frac{1}{3}\frac{|H(3\omega_0)|}{|H(\omega_0)|} = \frac{1}{3}\frac{\left|1+\sqrt{2}(1+\Delta_m)\cos\left((3\pi/4)(1+\Delta_p)\right)\right|}{\left|1+\sqrt{2}(1+\Delta_m)\cos\left((\pi/4)(1+\Delta_p)\right)\right|}$$

Magnitude and Phase Error Deviations

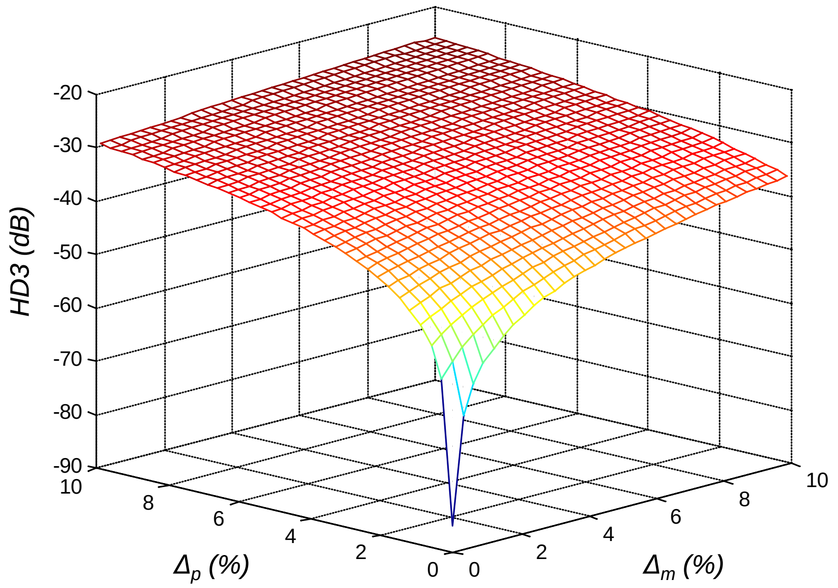
- Non-ideal effect
  - HD3 is monotonic to Δ_m and Δ_p
  - 20 dB better than conventional with 10% Δ_m and 5% Δ_p



Third Harmonic Distortion due to Non-Idealities

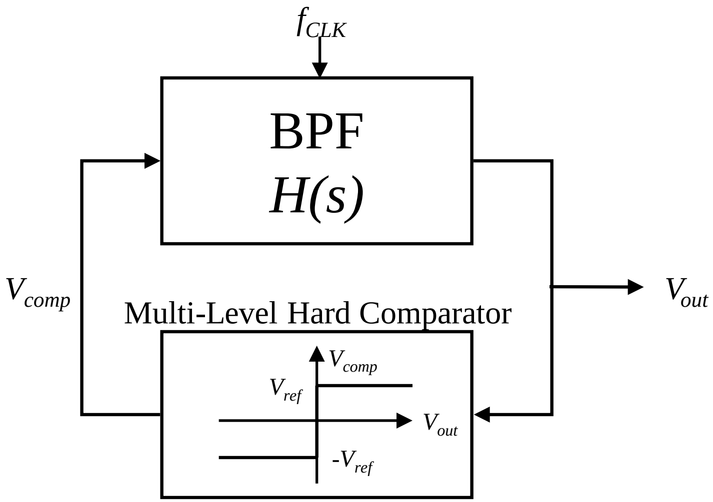
- ❑ Non-ideal effect

  - 3-d plot of HD3 vs. Δ_m and Δ_p



Continuous time BPF-based Oscillator

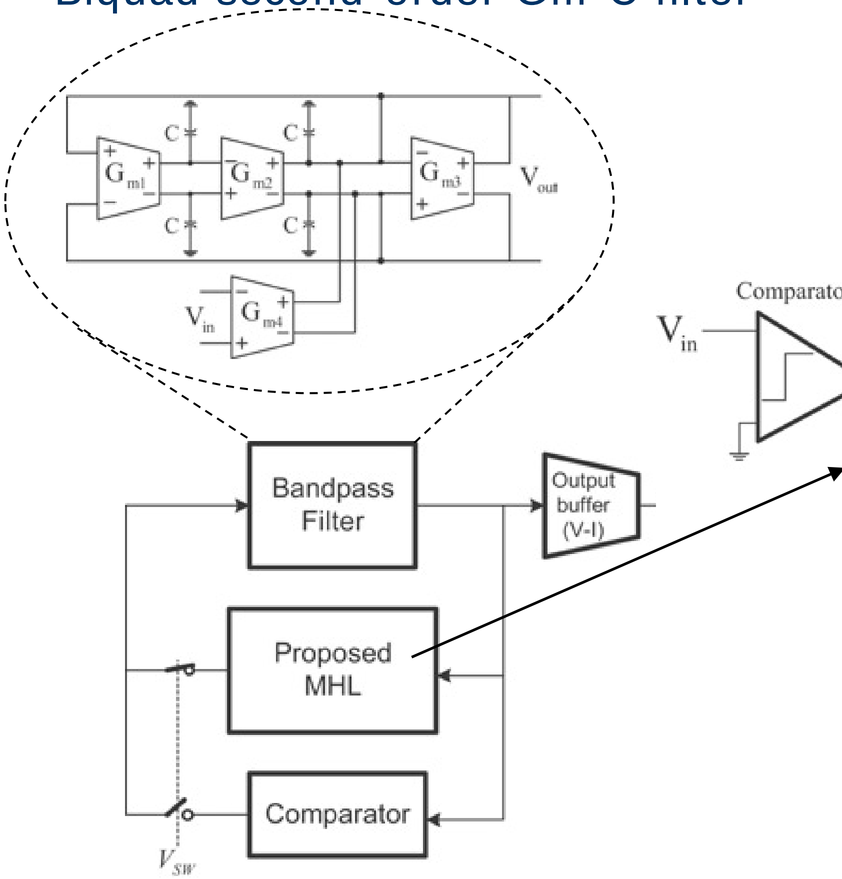
- ❑BPF-based oscillator
- ❑Filter
  - Biquad second-order Gm-C filter
  - f_o = 10 MHz, Q = 15

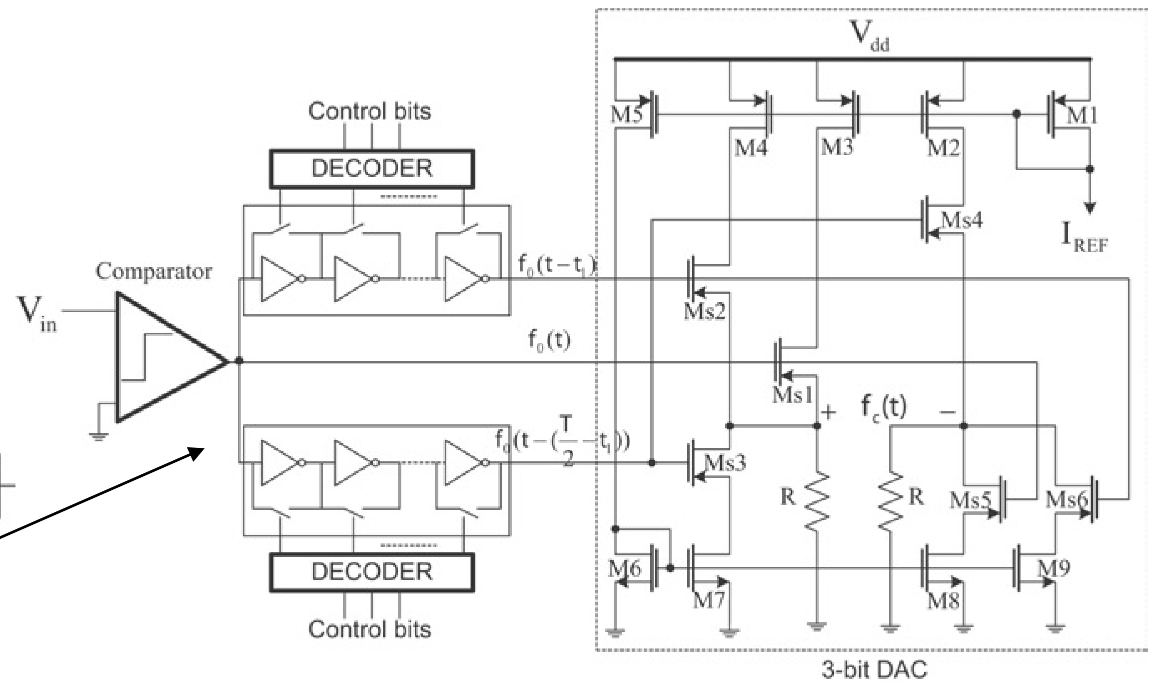


❑ F. Bahmani, E. Sánchez-Sinencio, “Low THD Bandpass-Based Oscillator Using Multilevel Hard Limiter,” IET Circuits, Devices and Systems, vol. 1, pp. 151-160, April 2007.

Implementation of the CT-BPF Based Oscillator

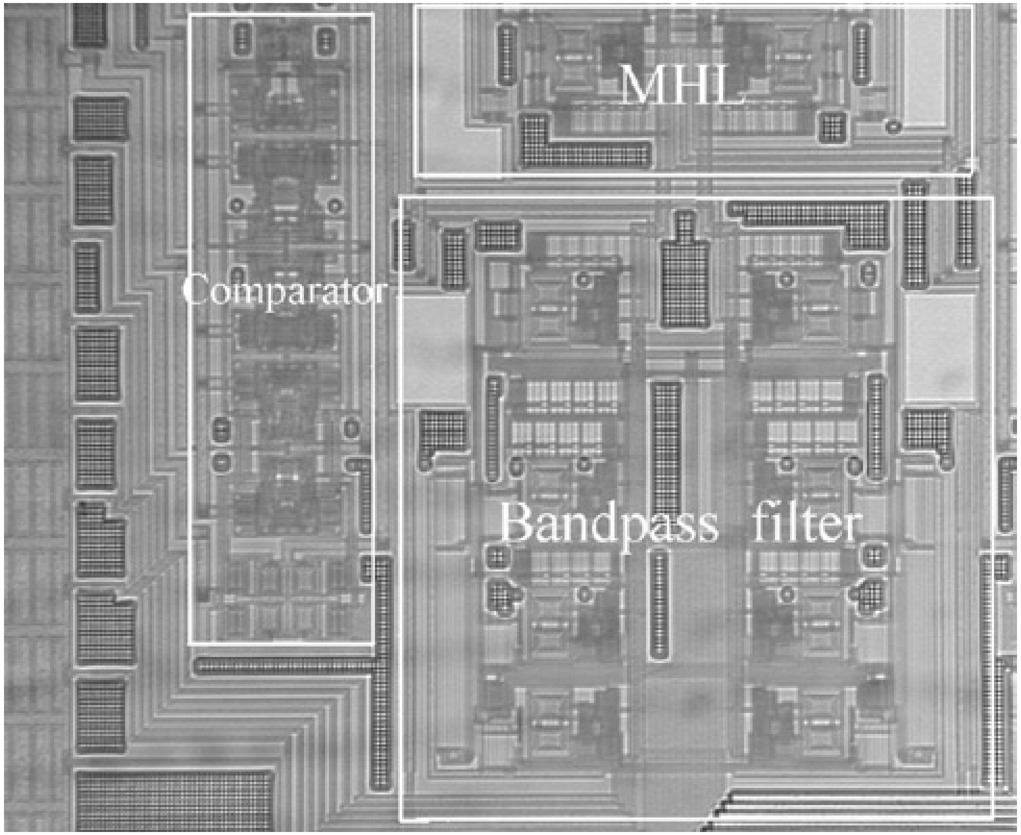
Biquad second-order Gm-C filter



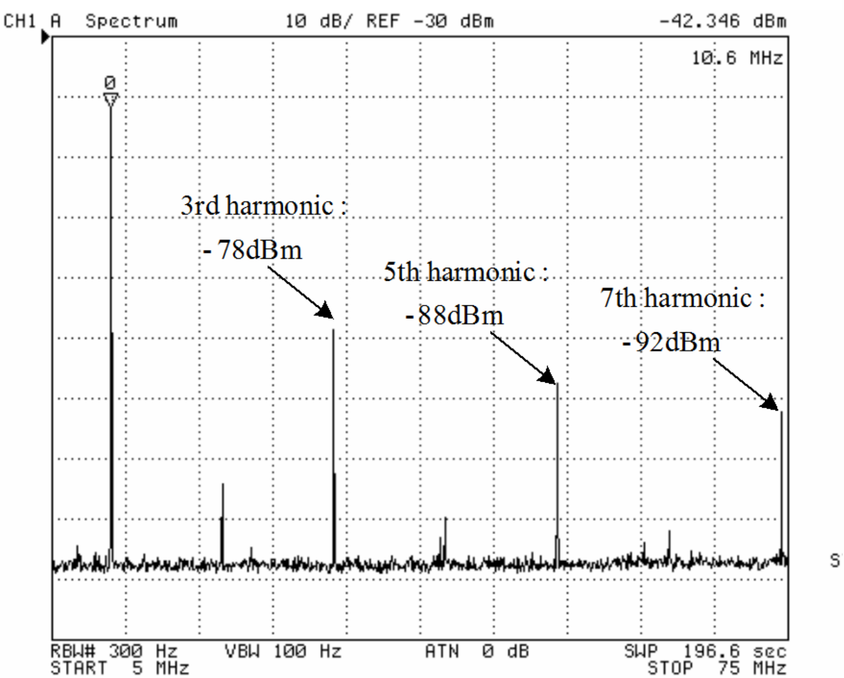


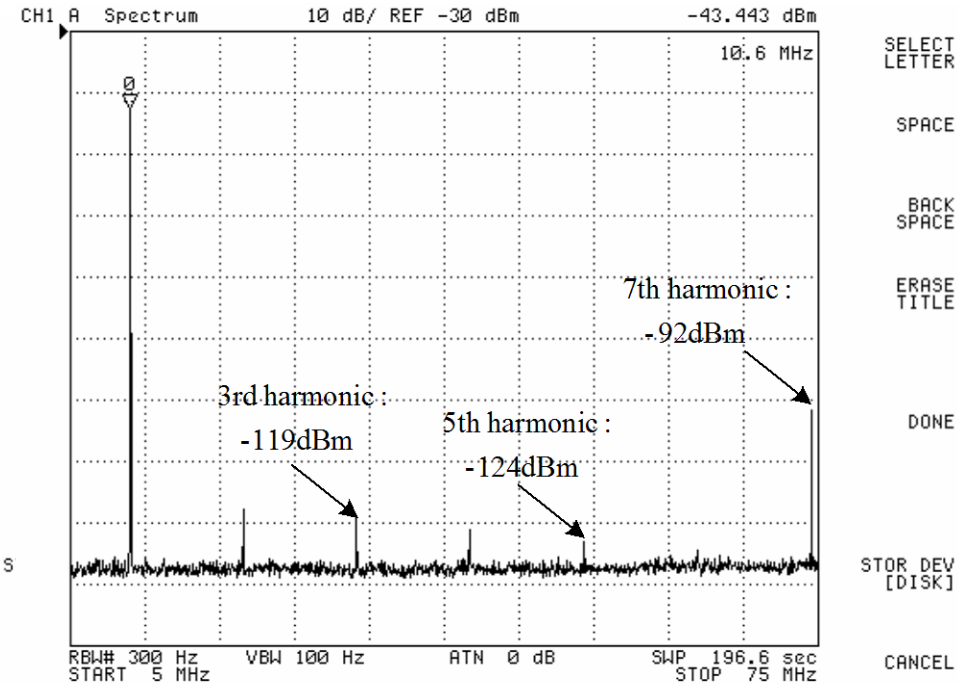
Multi-Level Hard Comparator

Chip Photograph



Experimental Results:
for comparison purposes we include a conventional and the proposed oscillator





THD=-39dB

Conventional

(2-level comparator)

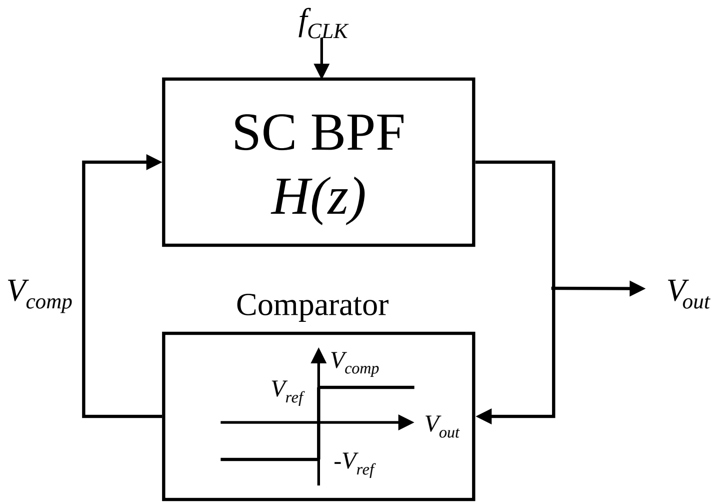
THD=-53dB

Proposed

(4-level comparator)

Switched Cap BPF-based Oscillator: Implementation and Experimental Results

- SC BPF-based oscillator
- BPF is implemented by Switched-Capacitor BPF
  - Biquad second-order BPF
  - f_{CLK} = 80 MHz, f_0 = 10 MHz, Q = 10

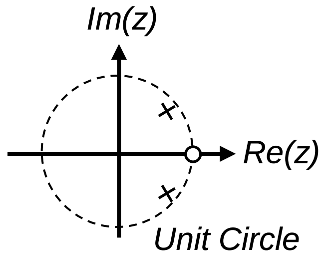


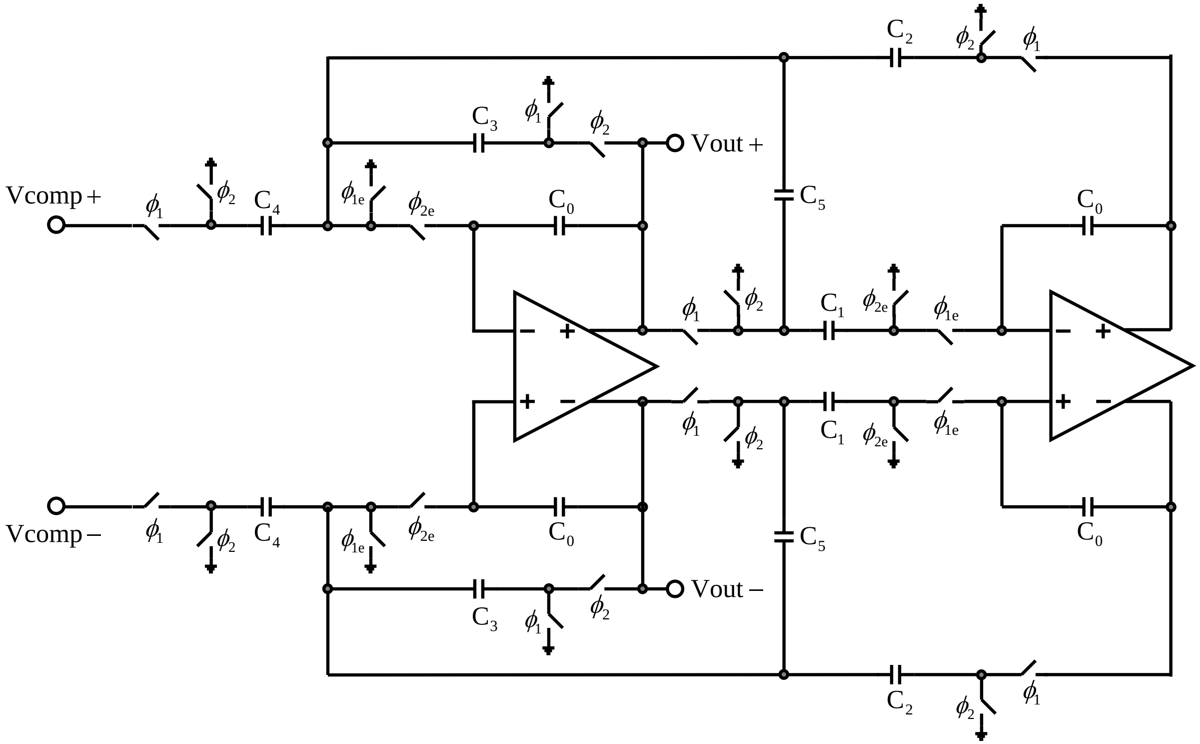
- S. W. Park, J. L. Ausín, F. Bahmani, E. Sánchez-Sinencio, "Non-Linear Shaping SC Oscillator with Enhanced Linearity," *IEEE Journal of Solid-State Circuits (JSSC)*, vol. 42, no. 11, pp. 2421-2431, Nov. 2007

Switched Capacitor BPF

- BPF schematic and transfer function

$$H(z)=\frac{K_4}{1+K_3}\frac{z^{-1}\left(1-z^{-1}\right)}{1+\frac{K_1K_2-K_3-K_5-2}{1+K_3}z^{-1}+\frac{1+K_5}{1+K_3}z^{-2}}$$

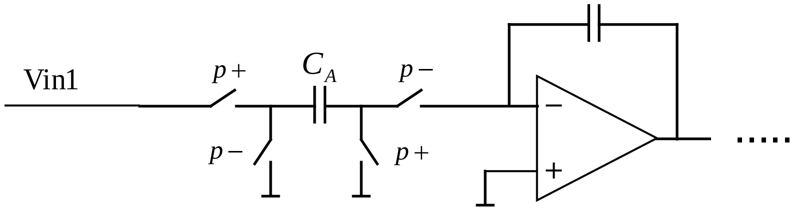


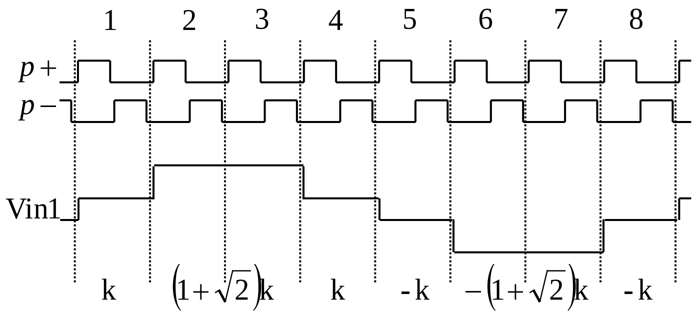


Switched Capacitor BPF

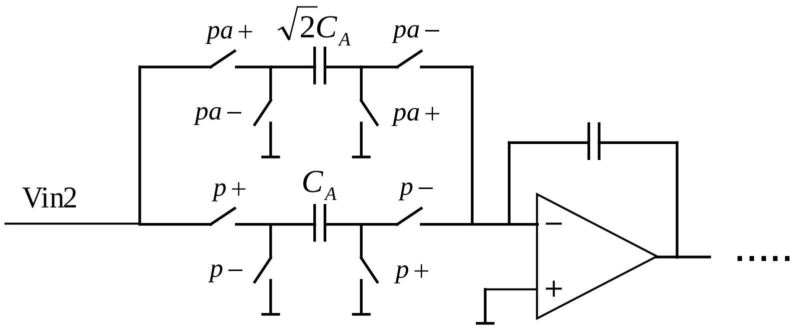
- ❑ Implementation with multi-level square wave

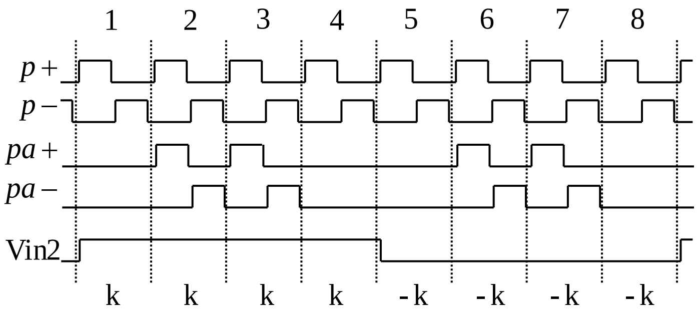
  - Conceptual implementation





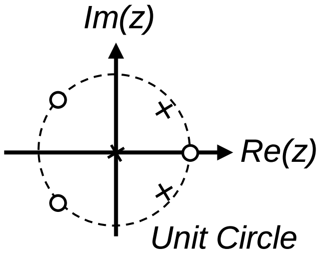
  - Actual implementation

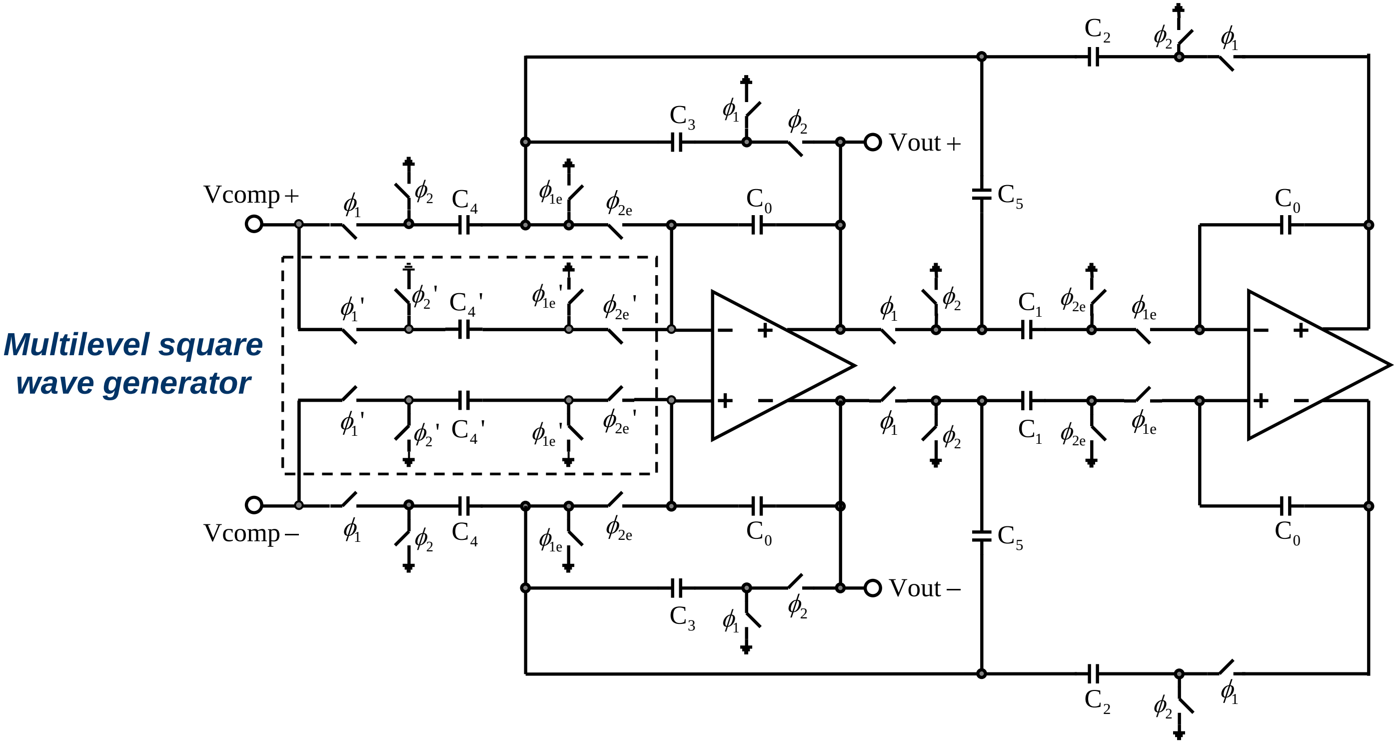




Proposed Multilevel SC Oscillator

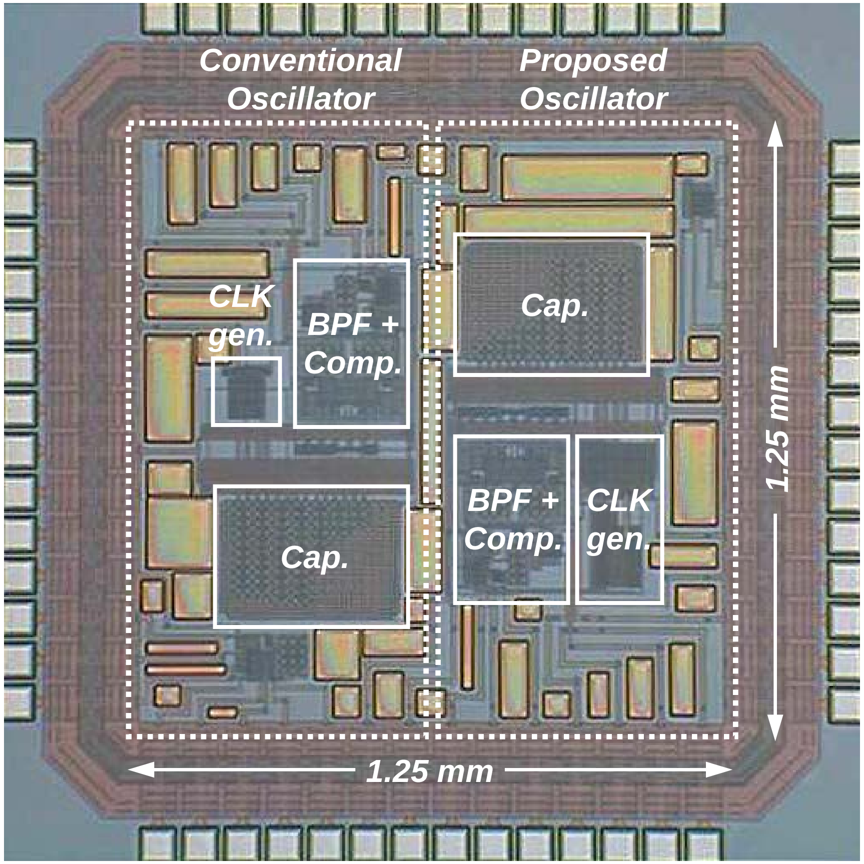
- ❑ Embedded multilevel square wave generator
- ❑ Work with conventional comparator

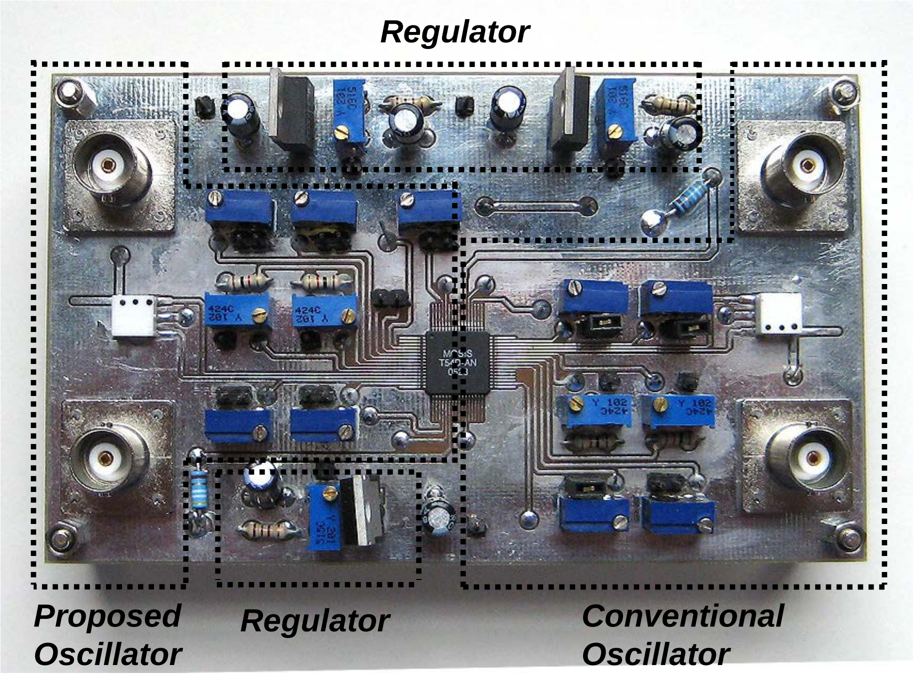




Chip and PCB Photograph of SC Oscillator

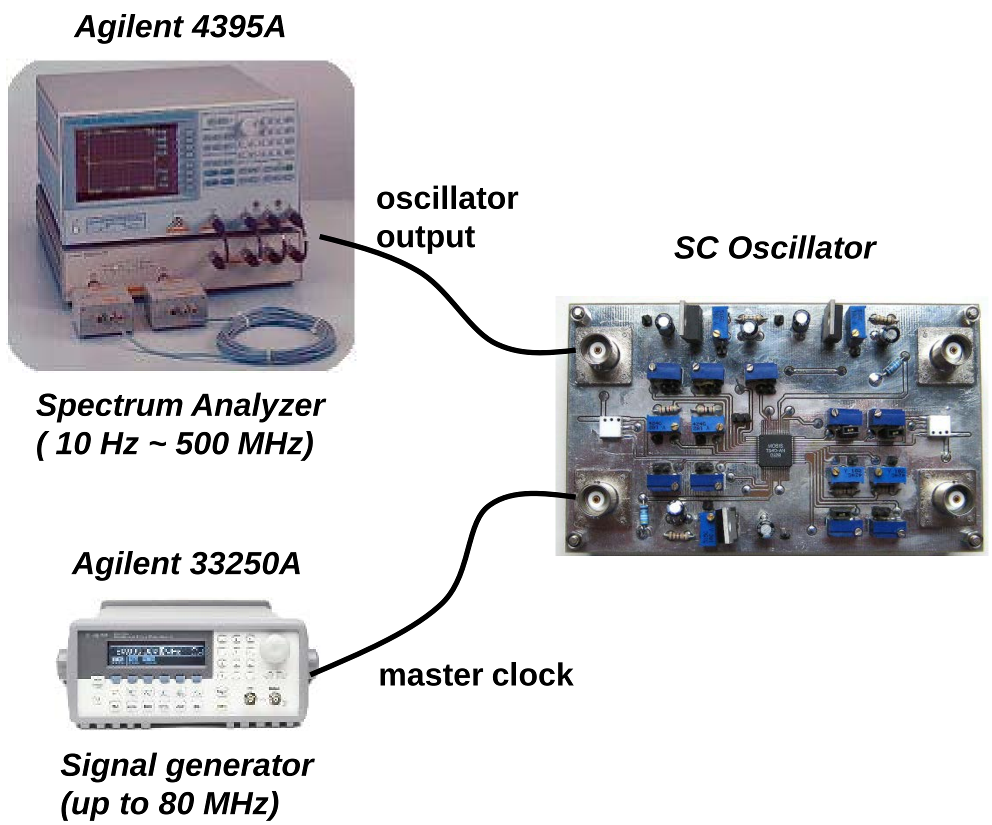
- TSMC 0.35um process
- TQFP-64 package





Measurement Setup

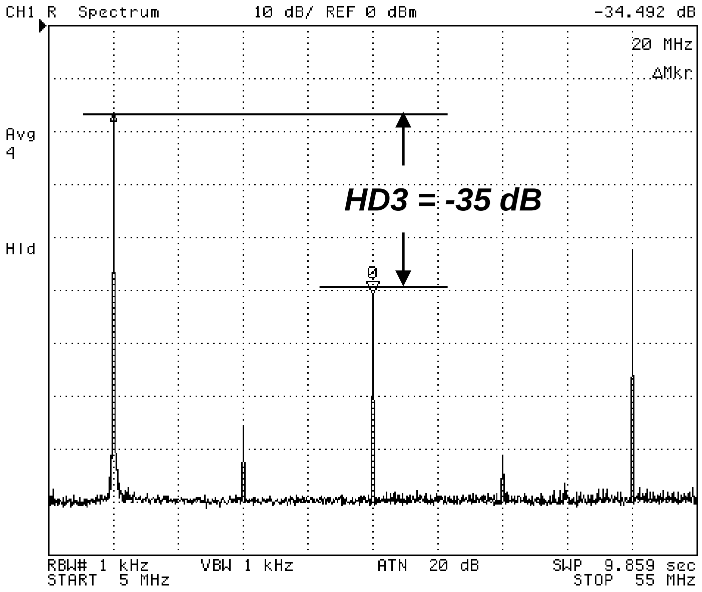
- Master clock : Agilent 33250A (~ 80 MHz)
- Spectrum analyzer : Agilent 4395A (~ 500 MHz)



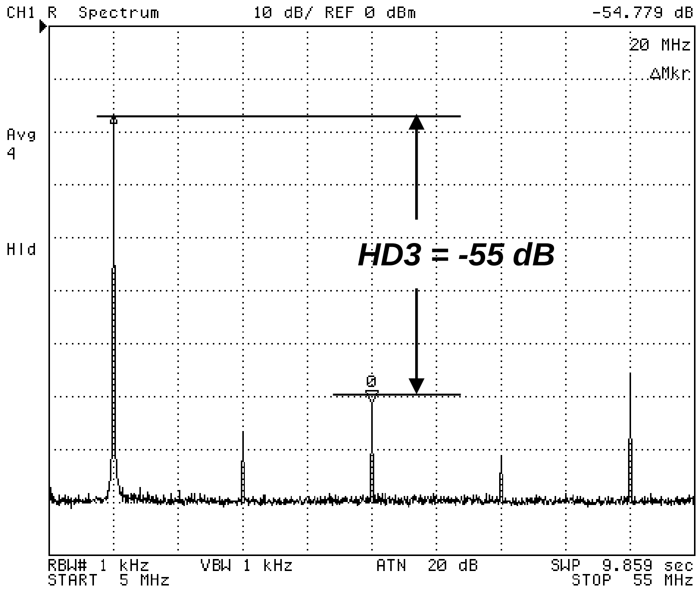
Experimental Result: SC Oscillators

- f_{CLK} = 80 MHz, f_0 = 10 MHz
- HD3 : 20 dB improvement over conventional

Conventional



Proposed



Performance Comparison

Parameters	This work (Proposed)	This work (Conventional)	ISCAS 2006	JSSC 2002	JSSC 2004
Maximum clock frequency	80 MHz	80 MHz	10 MHz	100 MHz	800 MHz
Maximum output frequency	10 MHz	10 MHz	1 MHz	25 MHz^{+}	400 MHz^{++}
Design Technique	SC BPF (2nd-order)	SC BPF (2nd-order)	SC BPF (4th-order)	DDFS	DDFS
Q-factor	10	10	85	N/A	N/A
THD, SFDR* @ Output frequency	-54.8 dB @ 10 MHz	-34.5 dB @ 10 MHz	-72 dB @ 1 MHz	42.1 dBc* @ 1.56 MHz	55 dBc* @ 8 MHz
Active area	0.2 mm^2	0.18 mm^2	0.12 mm^2	1.4 mm^2	1.47 mm^2
Technology	0.35 um CMOS	0.35 um CMOS	0.35 um CMOS	0.5 um CMOS	0.35 um CMOS
Power consumption	20.1 mW	19.8 mW	23 mW	8 mW	174 mW
Power supply	3.3 V	3.3 V	3 V	2.7 V	3.3 V

$^{+, ++}$ At the maximum output frequencies, SFDR is 17 dBc^{+} and 23 dBc^{++}.
* SFDR is presented instead of harmonic distortions.

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