VCO Fundamentals

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Mini-Circuits®

Overview

- Functional Block Concept
- Oscillator Review
- Basic Performance Metrics
- Methods of Tuning
- Advanced Performance Metrics
- Conclusion

Overview

- **Functional Block Concept**
  - **Applications**
  - **Specifications**
- Oscillator Review
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- Methods of Tuning
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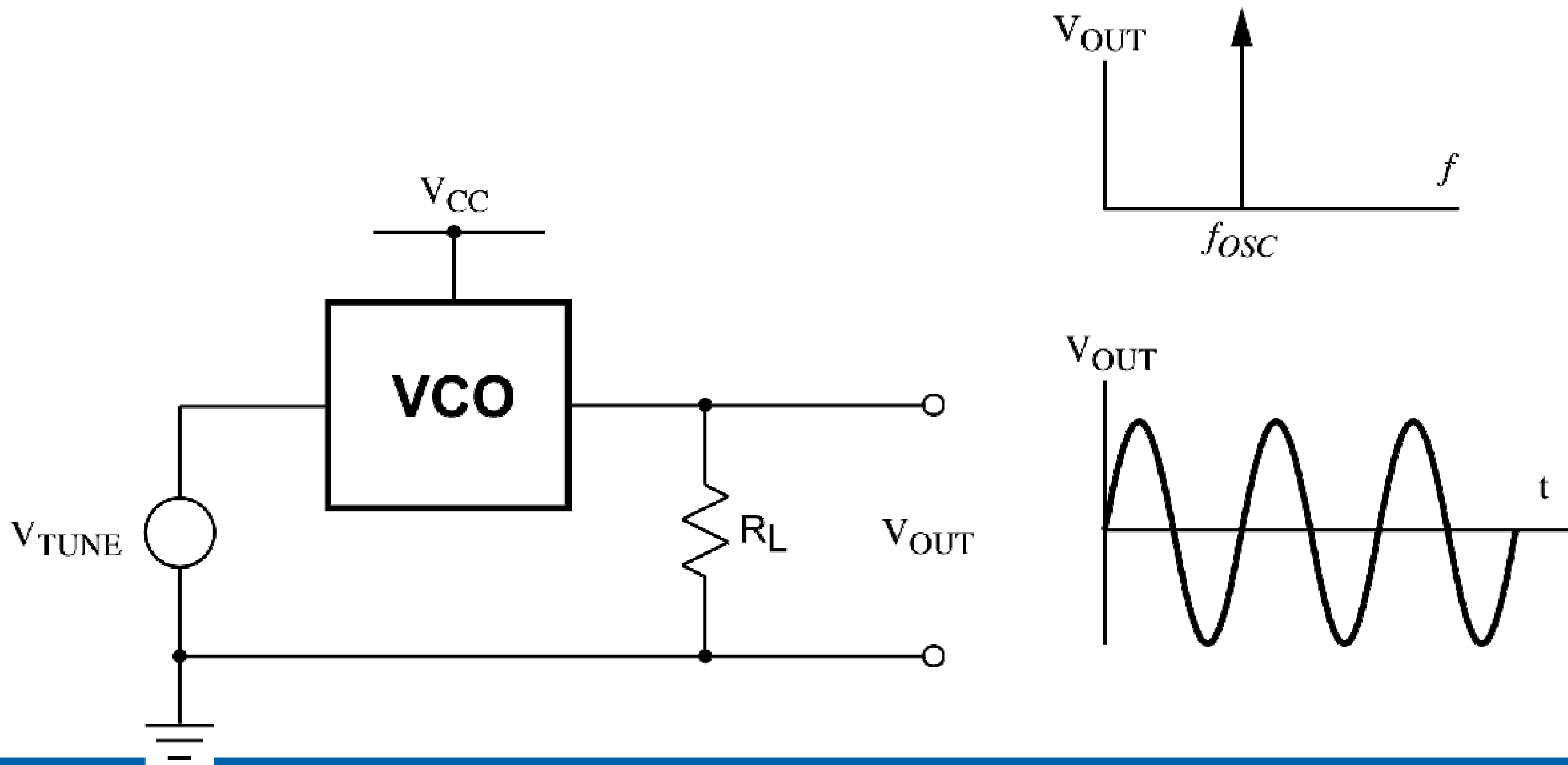
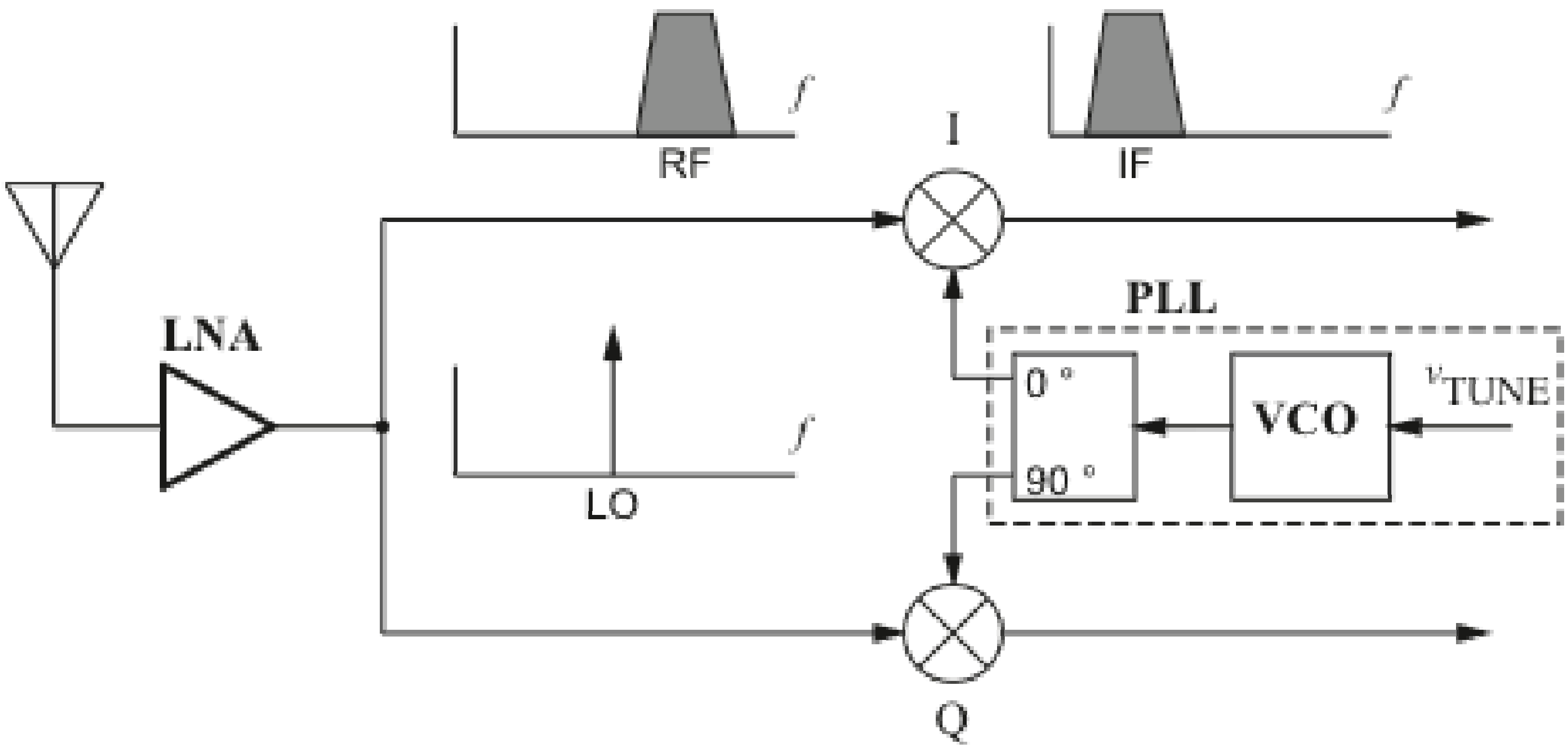
Functional Block Concept

- Input control voltage V_{TUNE} determines frequency of output waveform

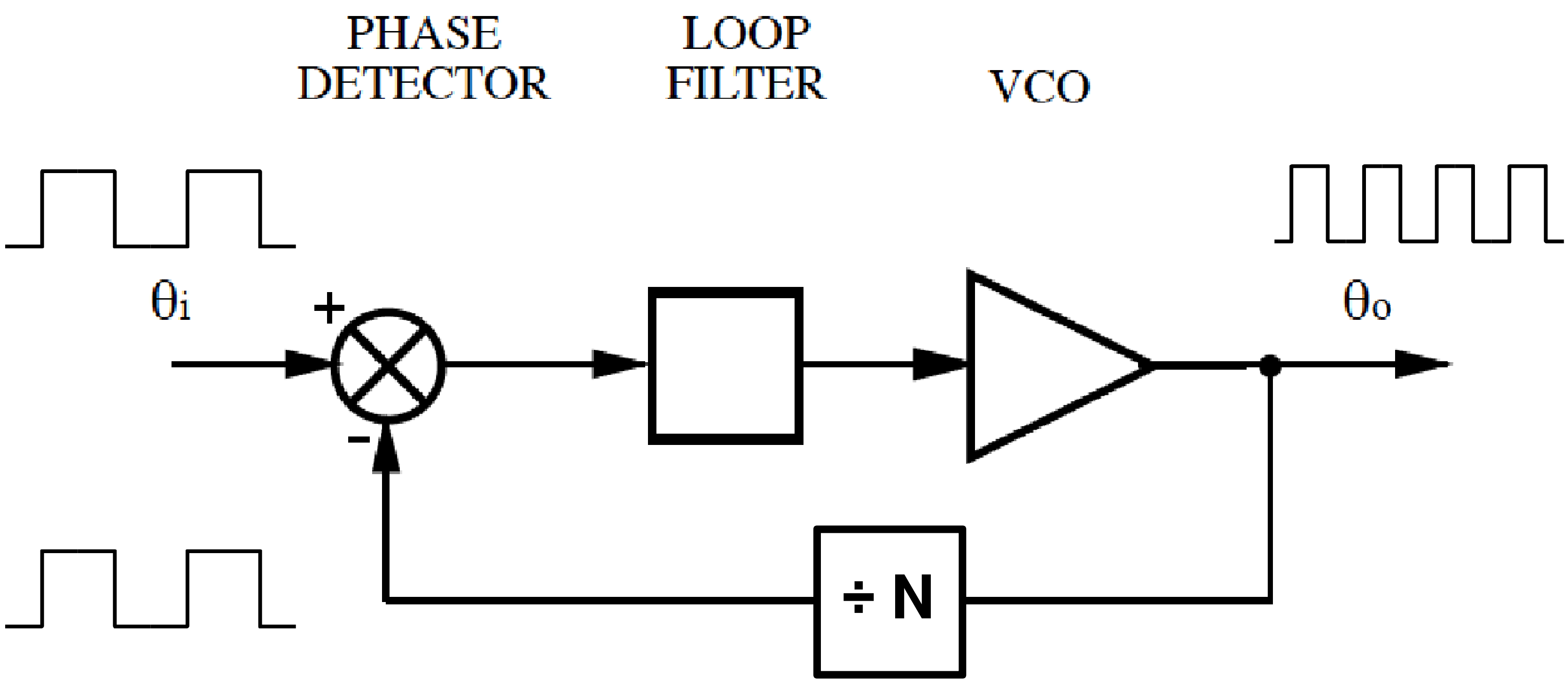


Applications: RF System



- Downconvert band of interest to IF
- VCO: Electrically tunable selection

Applications: Digital System



- **Clock synthesis (frequency multiplication)**

J. A. McNeill and D. R. Ricketts, "The Designer's Guide to Jitter in Ring Oscillators." Springer, 2009

Specifications

VOLTAGE CONTROLLED OSCILLATORS 50 Ω

12.5 MHz to 3 GHz

MOS Case CZ682 | ROS Case CK605, CK1113, CK829 | JTOS Case BK377 | JCOS Case BG419

MODEL PREFIX	FREQUENCY (MHz) Min.	FREQUENCY (MHz) Max.	POWER OUTPUT (dBm) Typ.	TUNE VOLTAGE (V) Min.	TUNE VOLTAGE (V) Max.	PHASE NOISE (dBc/Hz) SSB@ offset frequencies: Typ. 1 kHz	10 kHz	100 kHz	1 MHz	PULLING (MHz) pk-pk @12 dBr Typ.	PUSHING (MHz/V) Typ.	TUNING SENSITIVITY (MHz/V) Typ.	HARMONICS (dBc) Typ.	HARMONICS (dBc) Max.	3dB MOD. BANDWIDTH (kHz) Typ.	POWER SUPPLY Voltage (V) Nom.	POWER SUPPLY Current (mA) Max.
LINEAR TUNING *Wideband*																	
JCOS-175LN	125	175	+3.7	1.0	17.0	-95	-118	-138	-158	0.08	0.05	3-5	-25	-20	2900	12.0	20
JCOS-820BLN	807	832	+3.0	1.0	14.0	-88	-112	-132	-151	0.4	0.4	6.0	-24	-20	2000	10.0	25
JCOS-820WLN	780	860	+9.0	0.0	20.0	-90	-112	-132	-150	4.5	0.3	8.0	-13	-8	2000	9.0	25
JCOS-1100LN	1079	1114	+8.5	0.0	20.0	-88	-110	-130	-150	7.5	0.5	4.5	-15	-10	2000	8.0	25
JTOS-25	12.5	25	+8.0	1.0	11.0	-95	-115	-135	-155	0.03	0.02	1.0-4.0	-26	-13	130	12.0	20
JTOS-50	25	47	+8.5	1.0	15.0	-88	-108	-127	-147	0.06	0.04	2.0-2.6	-19	-12	50	12.0	20
JTOS-75	37.5	75	+8.0	1.0	16.0	-89	-110	-130	-140	0.15	0.11	2.8-4.0	-27	-20	125	12.0	20
JTOS-100	50	100	+8.3	1.0	16.0	-83	-108	-128	-140	0.6	0.2	3.7-4.8	-35	-20	100	12.0	18
JTOS-150	75	150	+9.5	1.0	16.0	-82	-106	-127	-147	0.8	0.3	5.8-6.7	-23	-17	112	12.0	20
JTOS-200	100	200	+10.0	1.0	16.0	-84	-105	-124	-145	1.0	0.2	6-10	-25	-20	110	12.0	20
JTOS-300	150	280	+9.0	1.0	16.0	-82	-102	-122	-142	1.0	0.2	9-14	-28	-20	120	12.0	20
JTOS-400	200	380	+9.0	1.0	16.0	-82	-102	-122	-142	1.4	0.4	10.5-17.1	-25	-20	130	12.0	20
JTOS-535	300	525	+9.5	1.0	16.0	-75	-97	-117	-137	2.0	0.5	10-24	-28	-20	115	12.0	20
JTOS-765	485	765	+8.0	1.0	16.0	-75	-98	-118	-138	2.0	0.5	20-30	-30	-20	100	12.0	20
JTOS-850VW	400	850	+6.0	0.5	18.0	-74	-96	-116	-136	6.0	1.5	15-80	-20	—	185	5.0	20
JTOS-1000W	500	1000	+7.0	1.0	18.0	-73	-94	-114	-134	5.0	1.0	30-40	-26	-20	100	12.0	25

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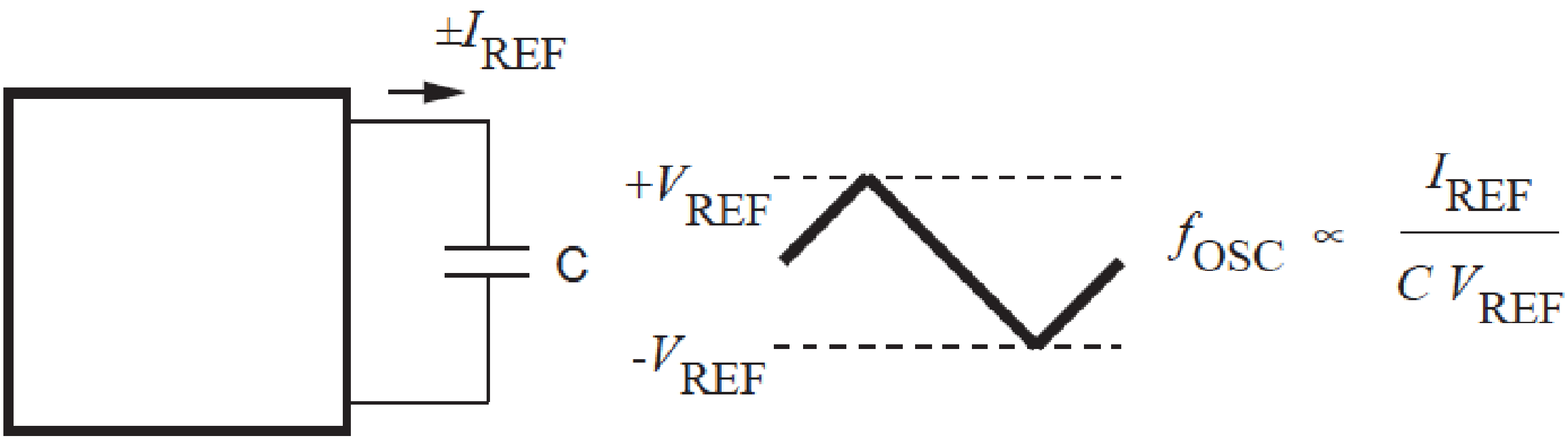
Overview

- Functional Block Concept
- **Oscillator Review**
  - **Frequency Control**
  - **Amplitude Control**
  - **Types of Oscillators**
- Basic Performance Metrics
- Methods of Tuning
- Advanced Performance Metrics
- Conclusion

Oscillator Review

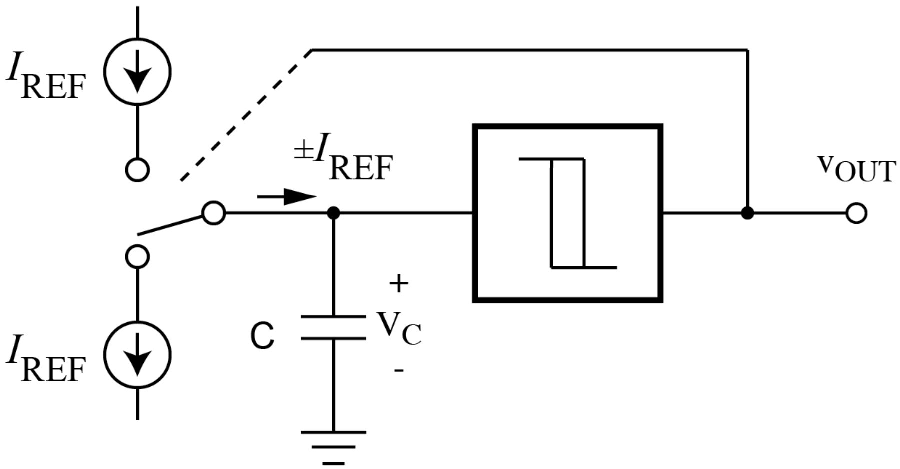
- Types of Oscillators
  - Multivibrator
  - Ring
  - Resonant
  - Feedback
- Basic Factors in Oscillator Design
  - Frequency
  - Amplitude / Output Power
  - Startup

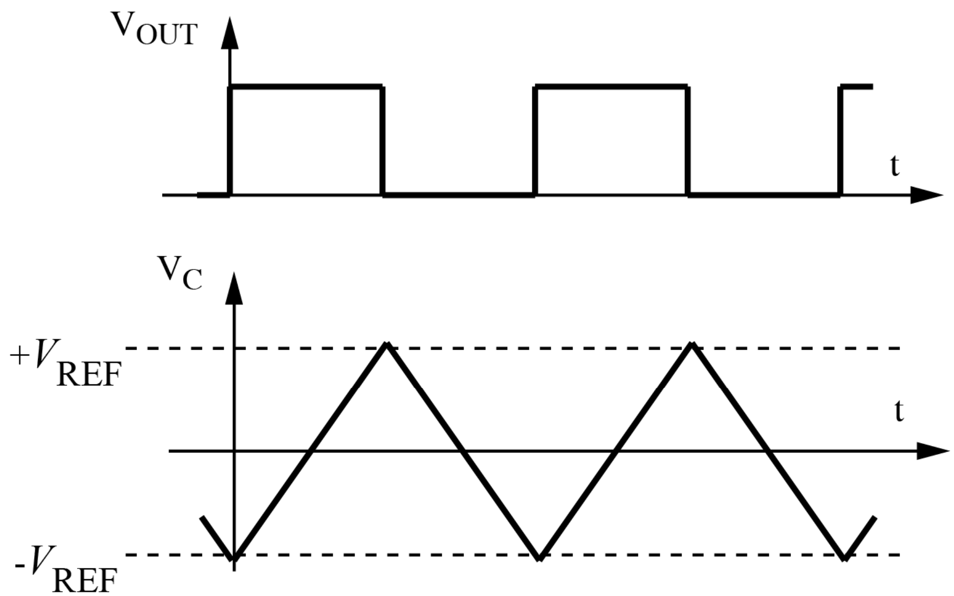
Multivibrator



- Conceptual multivibrator oscillator
  - Also called astable or relaxation oscillator
- One energy storage element

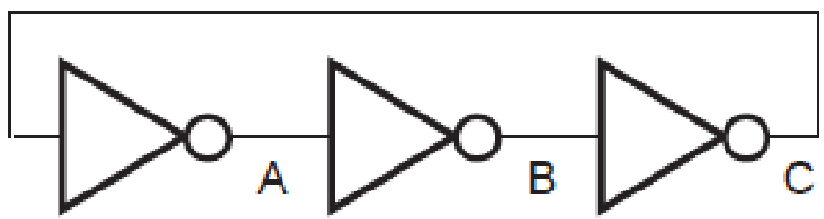
Example: Multivibrator

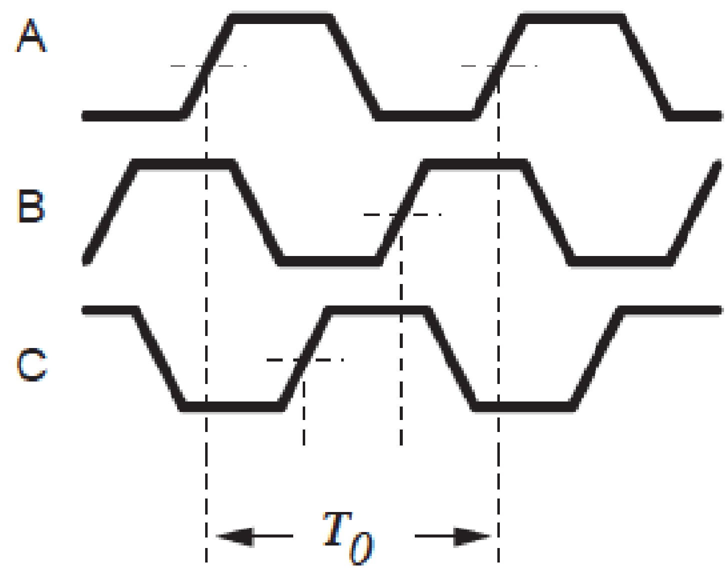




- **Frequency: Controlled by charging current I_{REF}, C, V_{REF} thresholds**
- **Amplitude: Controlled by thresholds, logic swing**
- **Startup: Guaranteed; no stable state**

Ring Oscillator

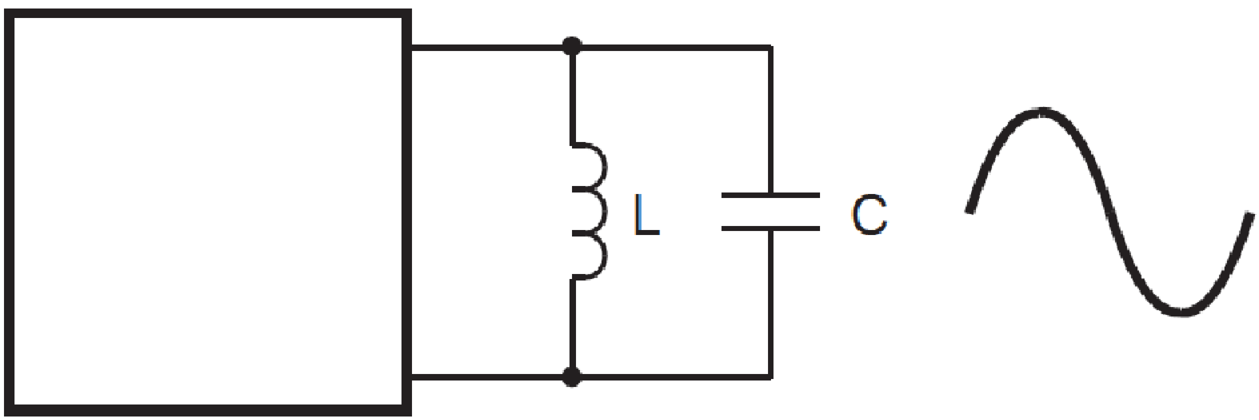




- **Frequency: Controlled by gate delay**
- **Amplitude: Controlled by logic swing**
- **Startup: Guaranteed; no stable state**

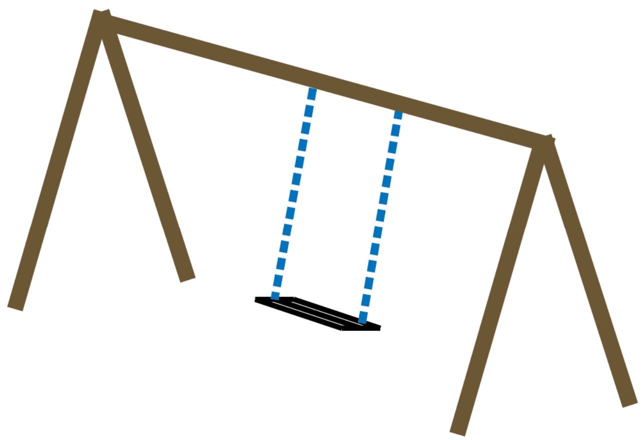
Resonant Oscillator

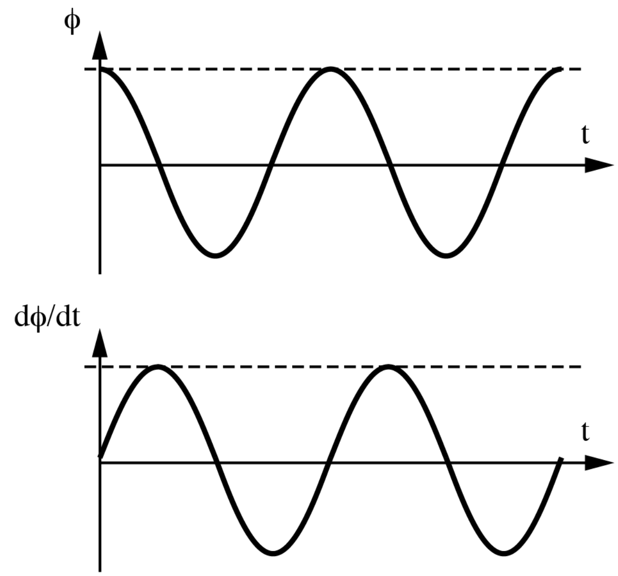
- **Concept: Natural oscillation frequency of resonance**
- **Energy flows back and forth between two storage modes**



$$f_{OSC} = \frac{1}{2\pi\sqrt{LC}}$$

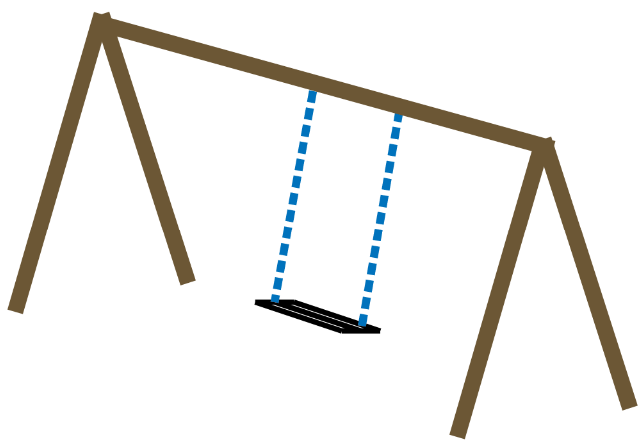
Resonant Oscillator (Ideal)

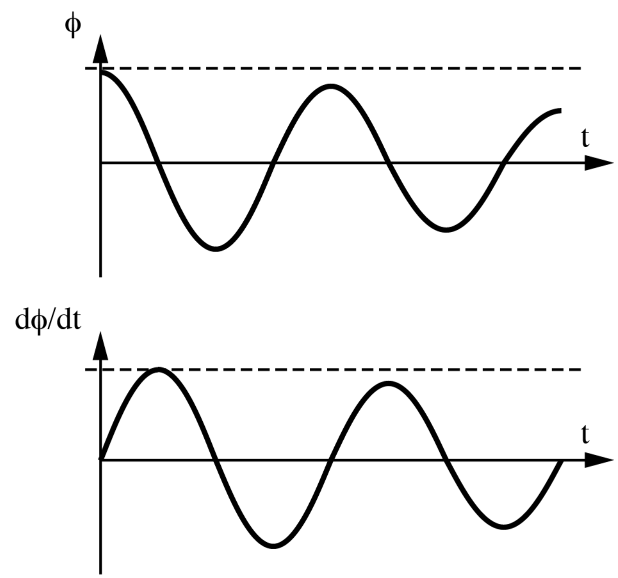




- Example: swing (ideal)
- Energy storage modes: potential, kinetic
- Frequency: Controlled by length of pendulum
- Amplitude: Controlled by initial position
- Startup: Needs initial condition energy input

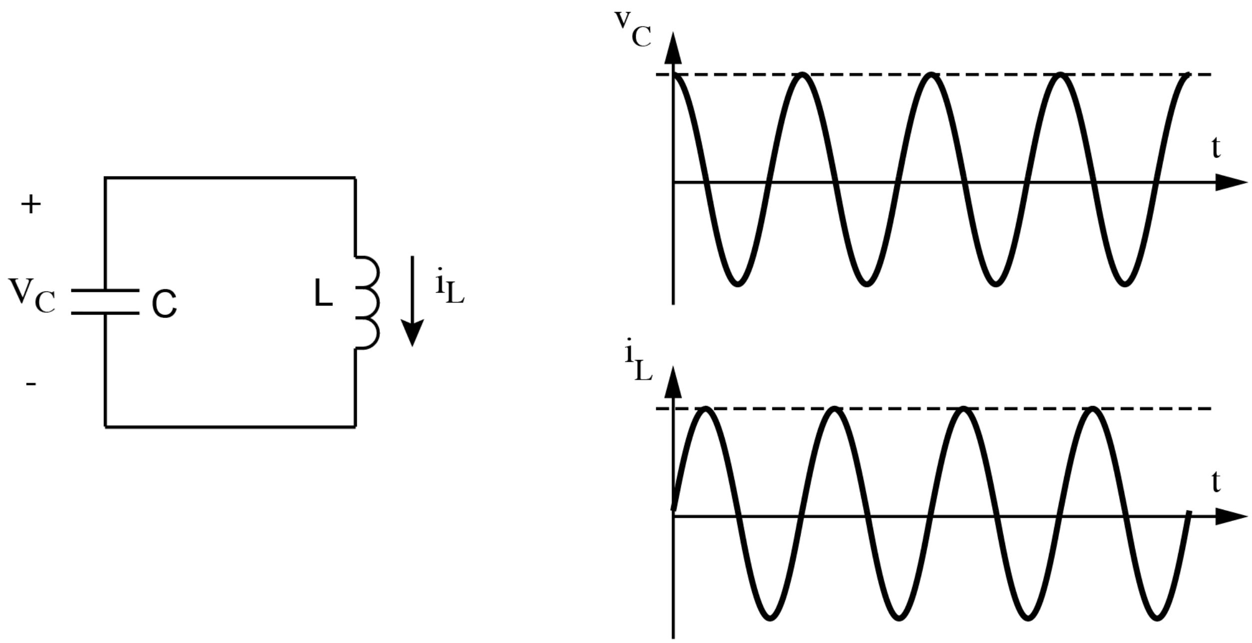
Resonant Oscillator (Real)





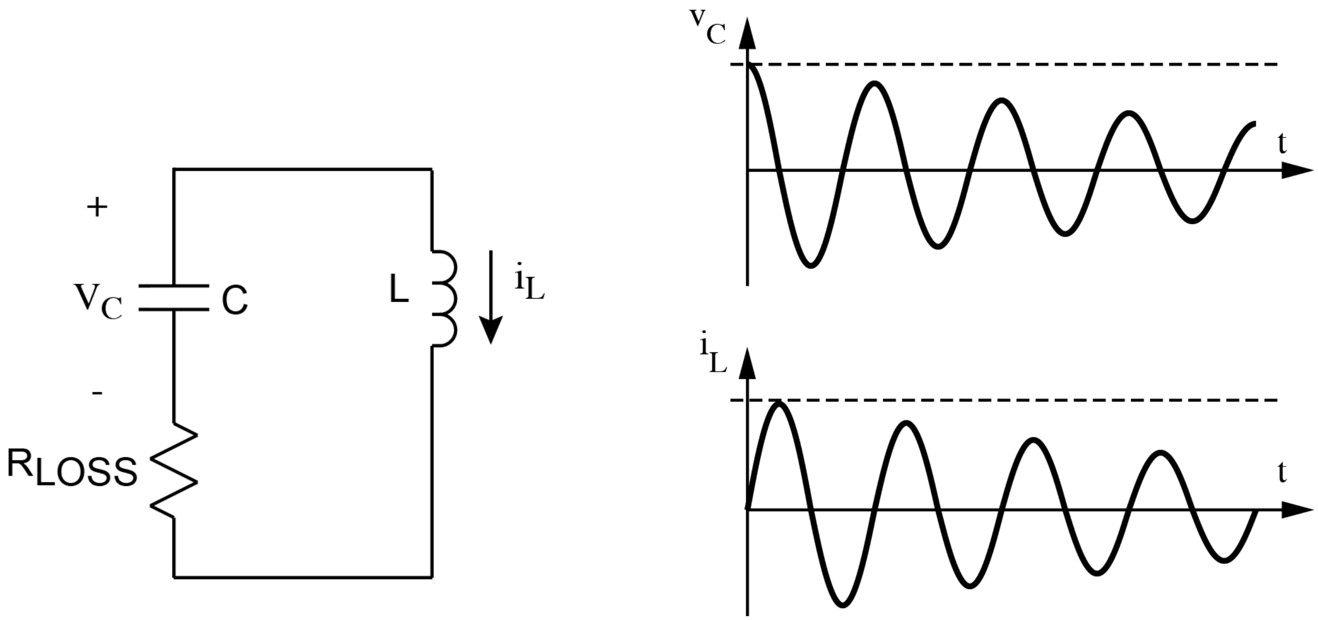
- **Problem: Loss of energy due to friction**
- **Turns “organized” energy (potential, kinetic) into “disorganized” thermal energy (frictional heating)**
- **Amplitude decays toward zero**
- **Requires energy input to maintain amplitude**
- **Amplitude controlled by “supervision”**

LC Resonant Oscillator (Ideal)



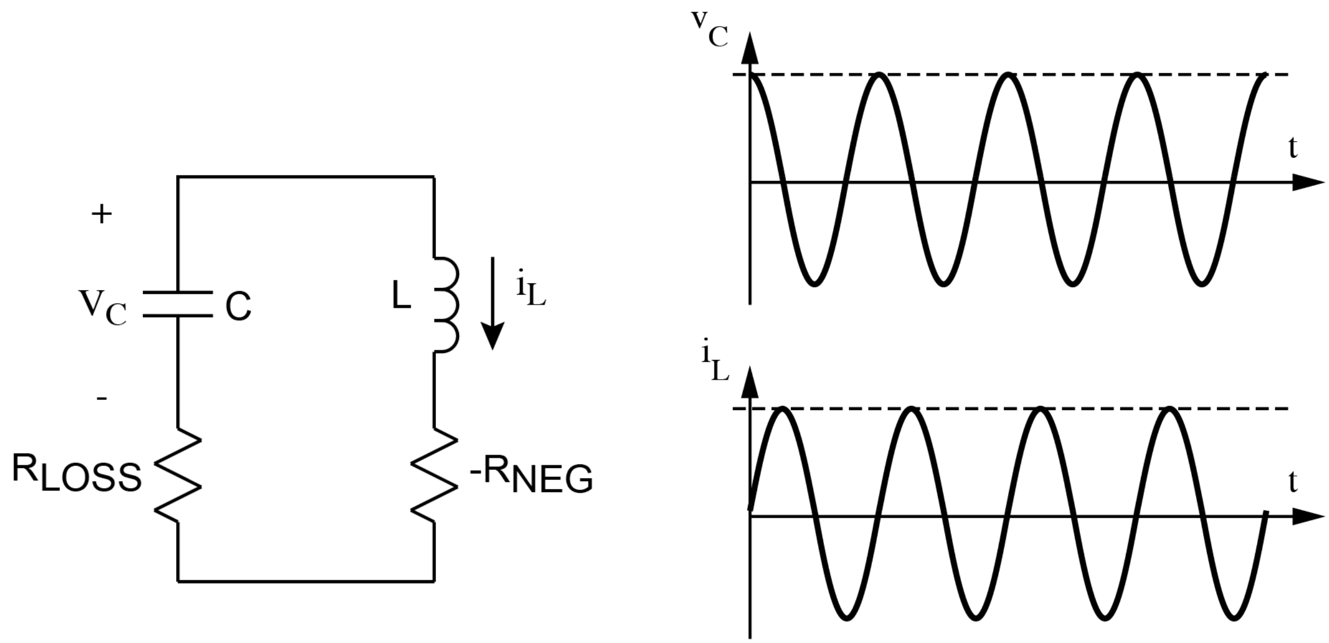
- **Energy storage modes:**
  Magnetic field (L current), Electric field (C voltage)
- **Frequency: Controlled by LC**
- **Amplitude: Controlled by initial condition**
- **Startup: Needs initial energy input (initial condition)**

LC Resonant Oscillator (Real)



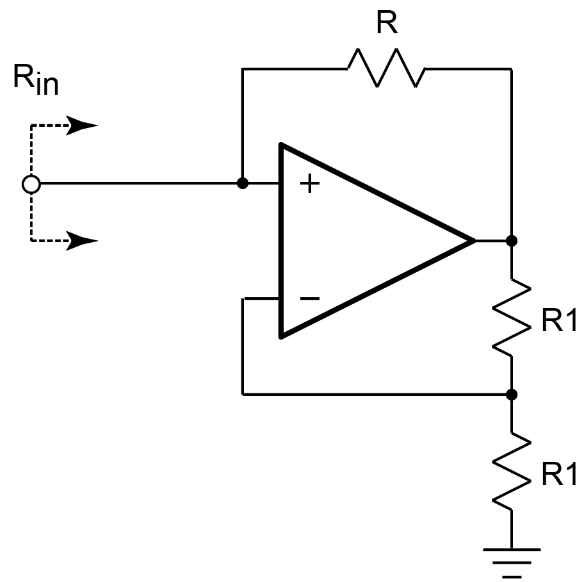
- **Problem: Loss of energy due to nonideal L, C**
  - **Model as resistor R_{LOSS}; Q of resonator**
- **E, M field energy lost to resistor heating**
- **Amplitude decays toward zero**

LC Resonant Oscillator (Real)



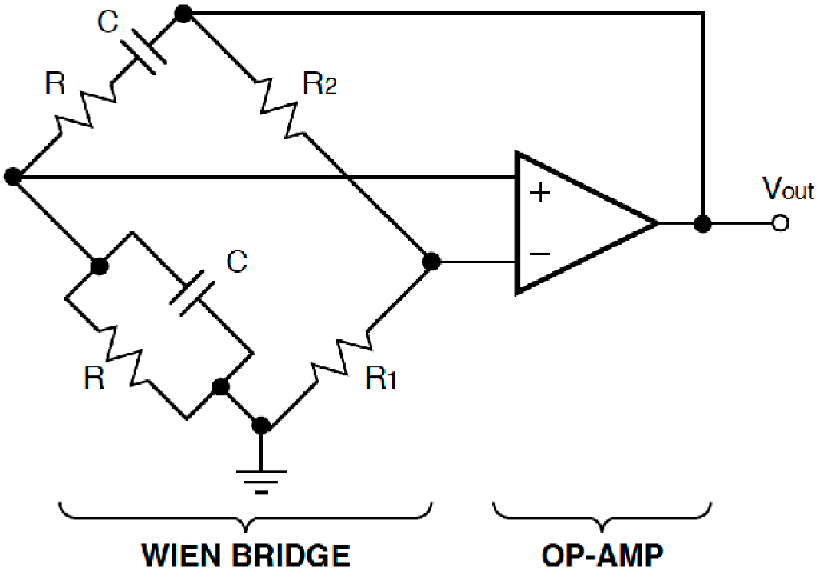
- **Problem: Loss of energy due to nonideal L, C**
- **Requires energy input to maintain amplitude**
- **Synthesize “negative resistance”**
- **Cancel R_{LOSS} with $-R_{NEG}$**

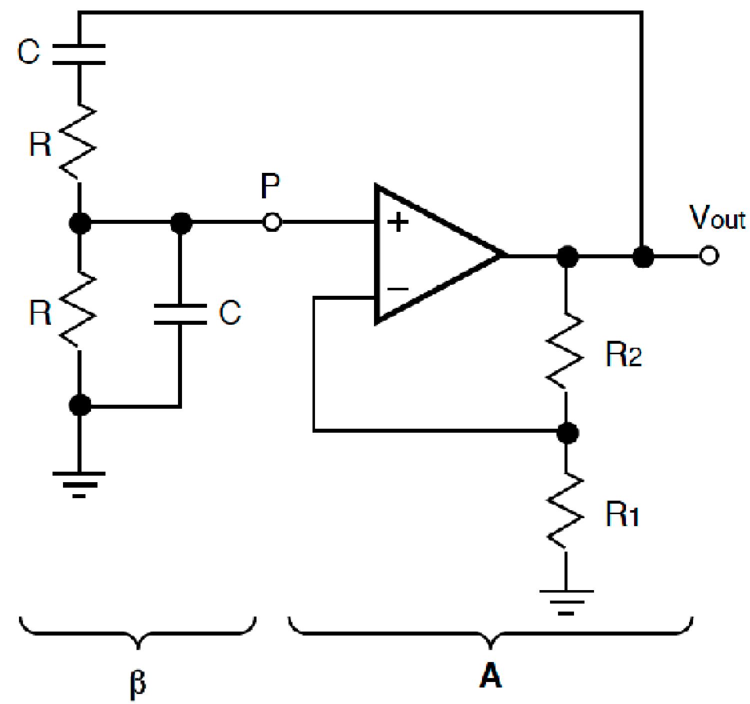
Negative Resistance



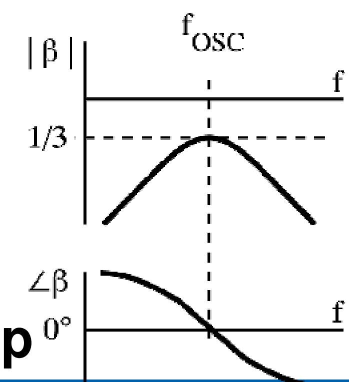
- Use active device to synthesize V-I characteristic that "looks like" $-R_{NEG}$
- Example: amplifier with positive feedback
- Feeds energy into resonator to counteract losses in R_{LOSS}

Feedback Oscillator: Wien Bridge

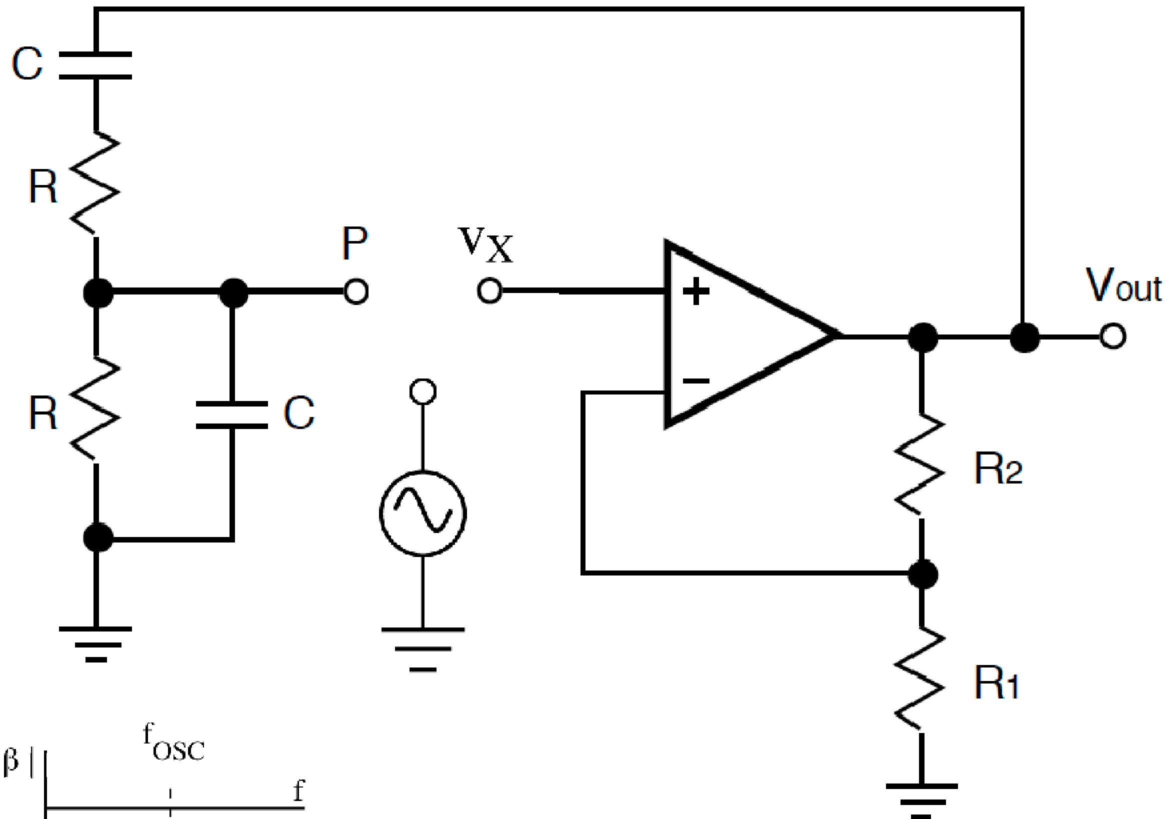


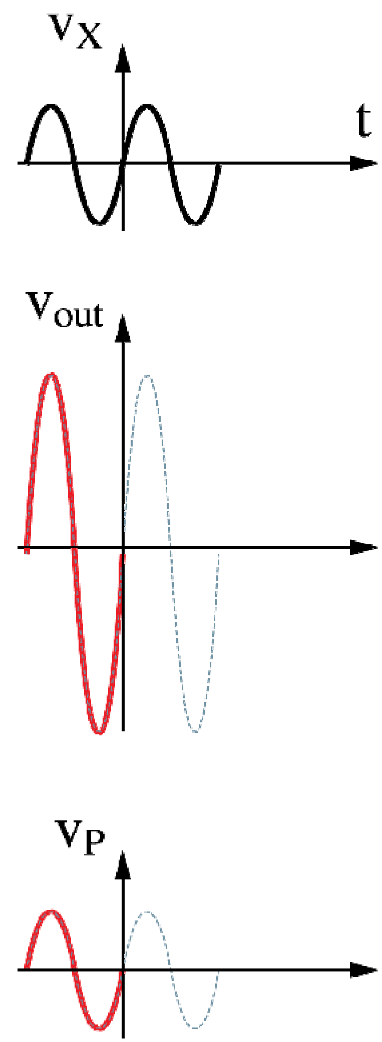


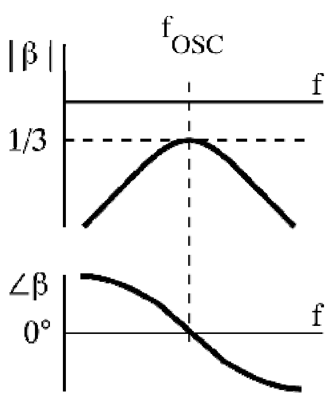
- **Forward gain A=3**
- **Feedback network with transfer function β(f)**
- **At f_{OSC}, |β|=1/3 and ∠β =0**
- **Thought experiment:**
  break loop, inject sine wave, look at signal returned around feedback loop



$A\beta=1$

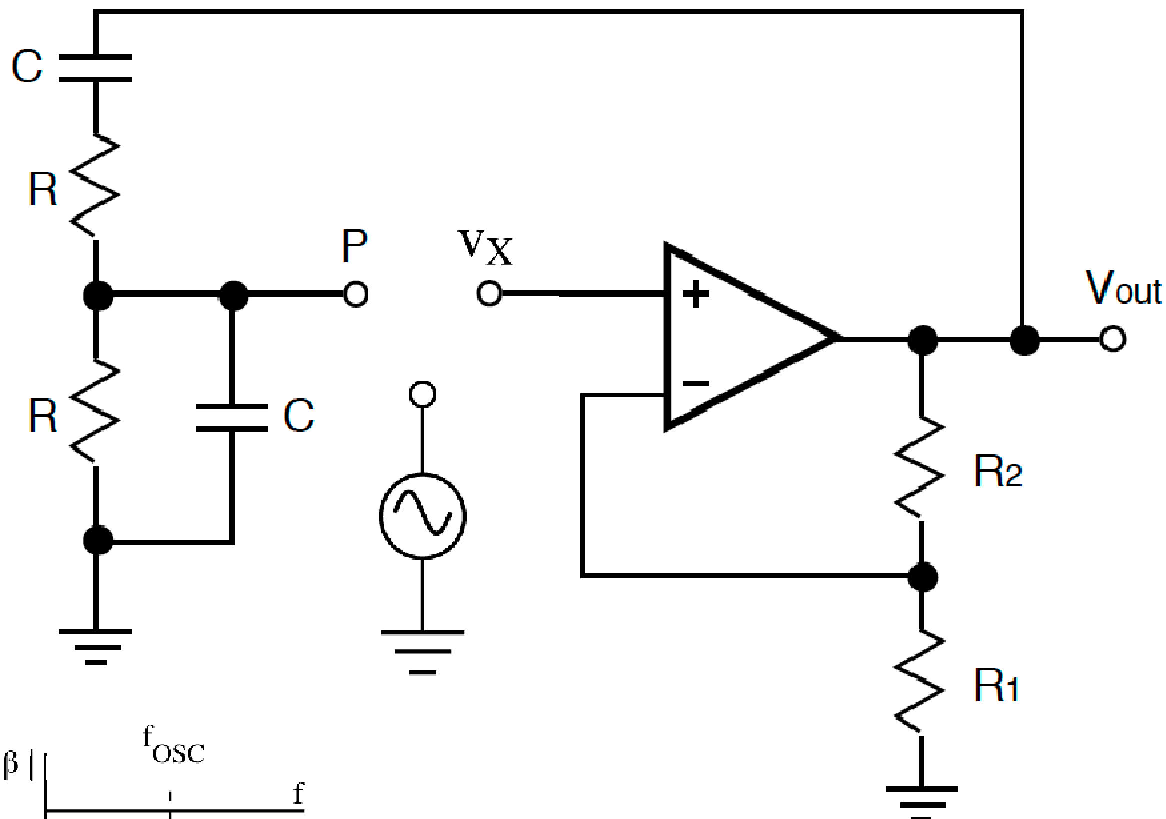


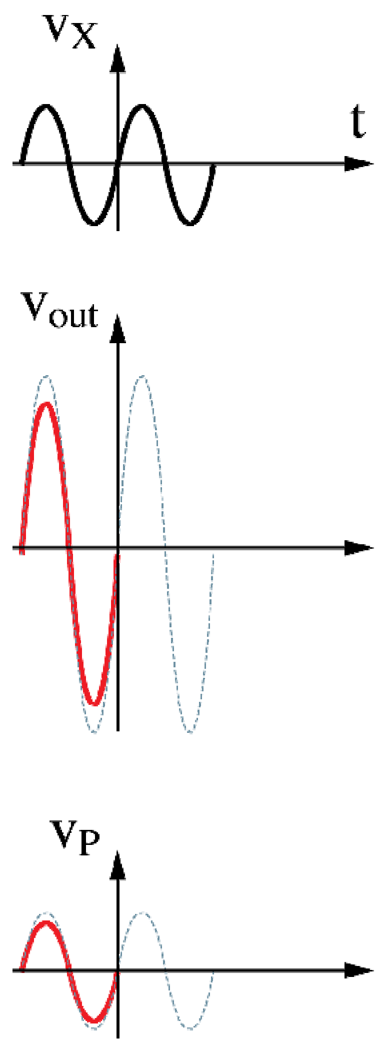


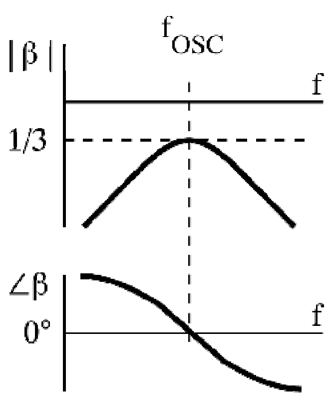


- **“Just right” waveform is self sustaining**

Aβ=0.99

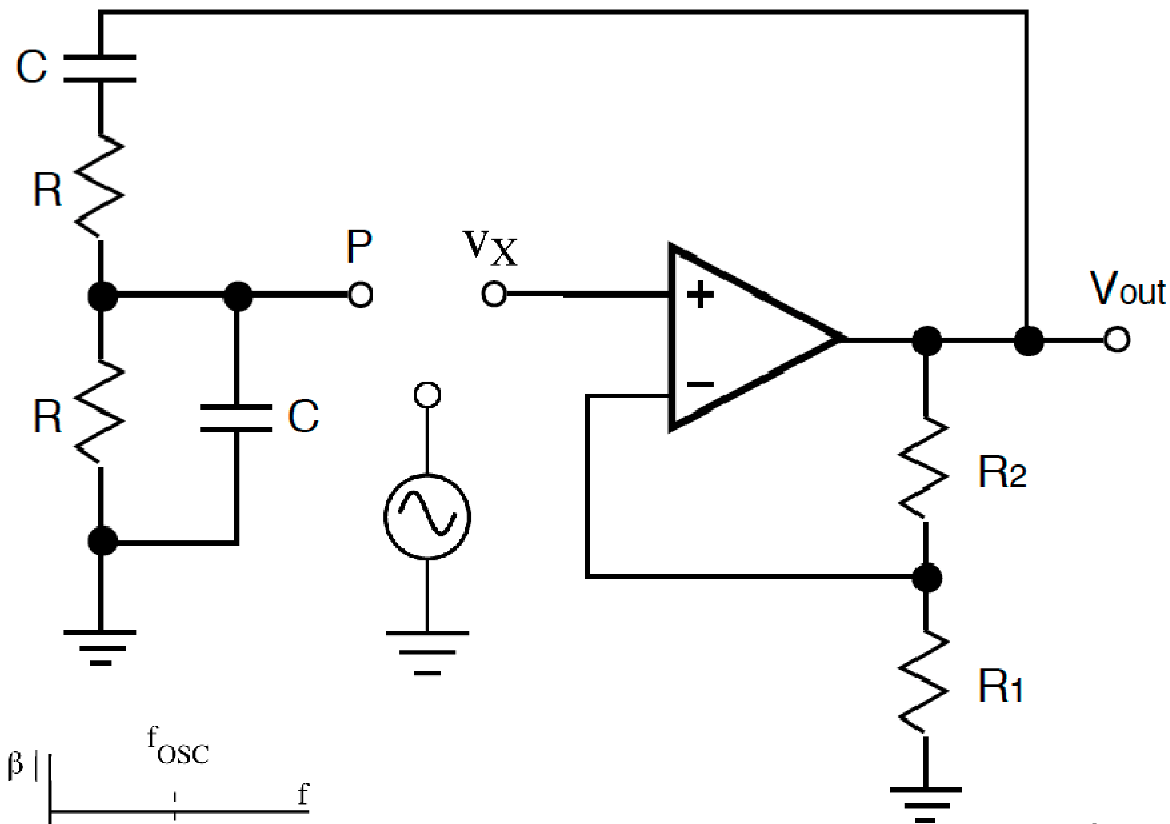


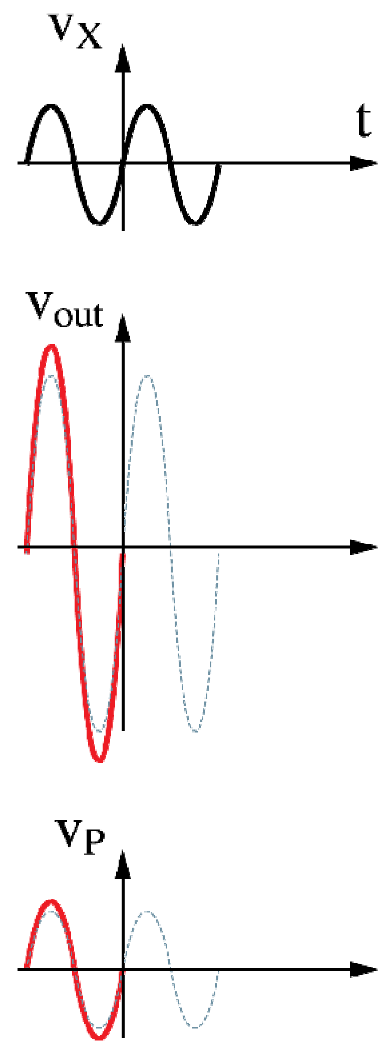


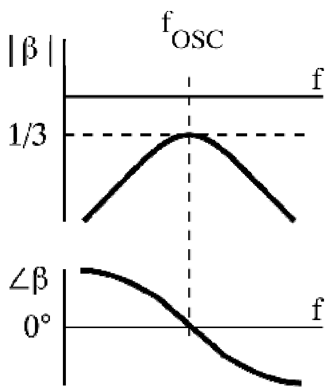


- **“Not enough” waveform decays to zero**

$A\beta=1.01$

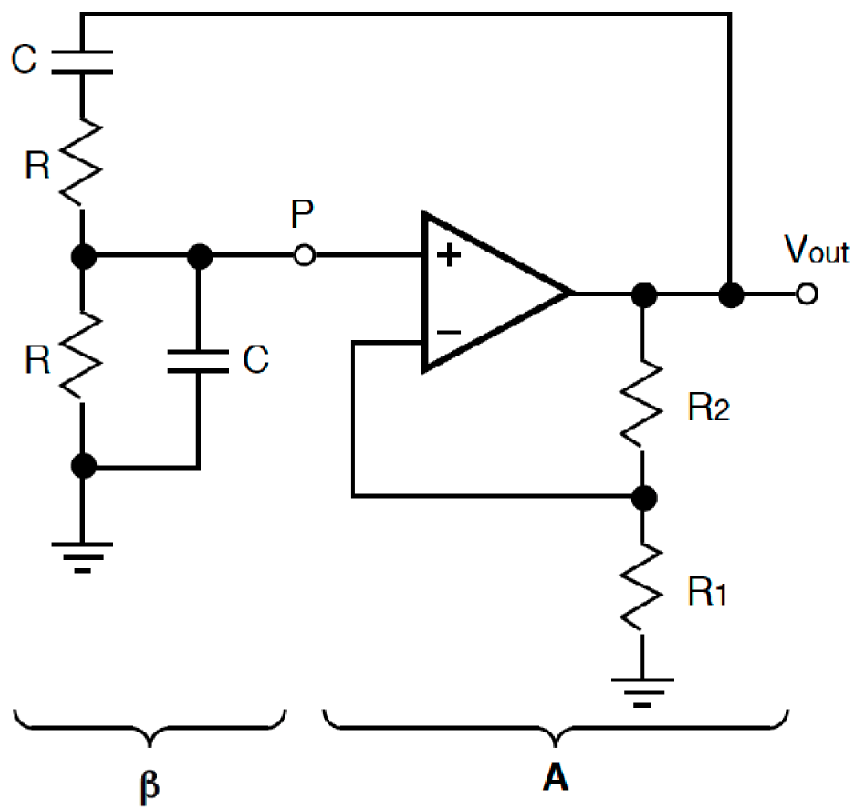






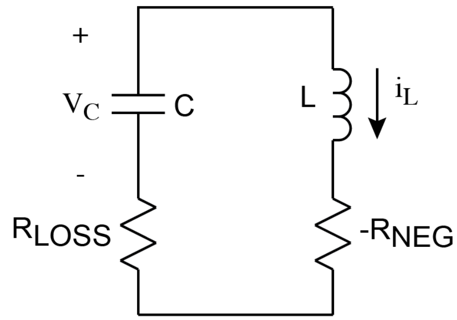
- **"Too much" waveform grows exponentially**

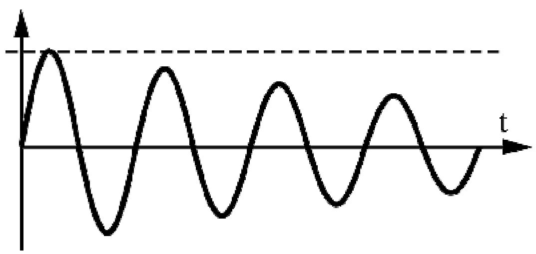
Feedback oscillator



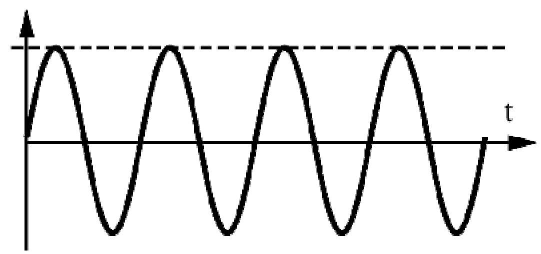
- Stable amplitude condition: Aβ=1 EXACTLY
- Frequency determined by feedback network Aβ=1 condition
- Need supervisory circuit to monitor amplitude
- Startup: random noise; supervisory circuit begins with Aβ>1

Resonant Oscillator (Real)

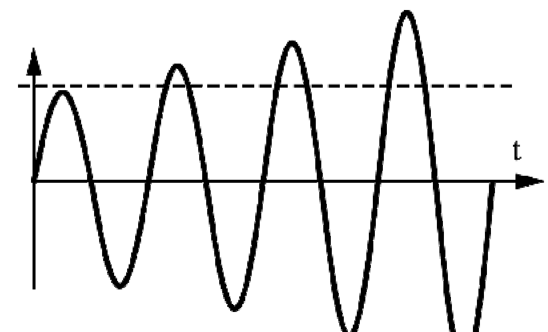




$|R_{NEG}| < R_{LOSS}$



$|R_{NEG}| = R_{LOSS}$



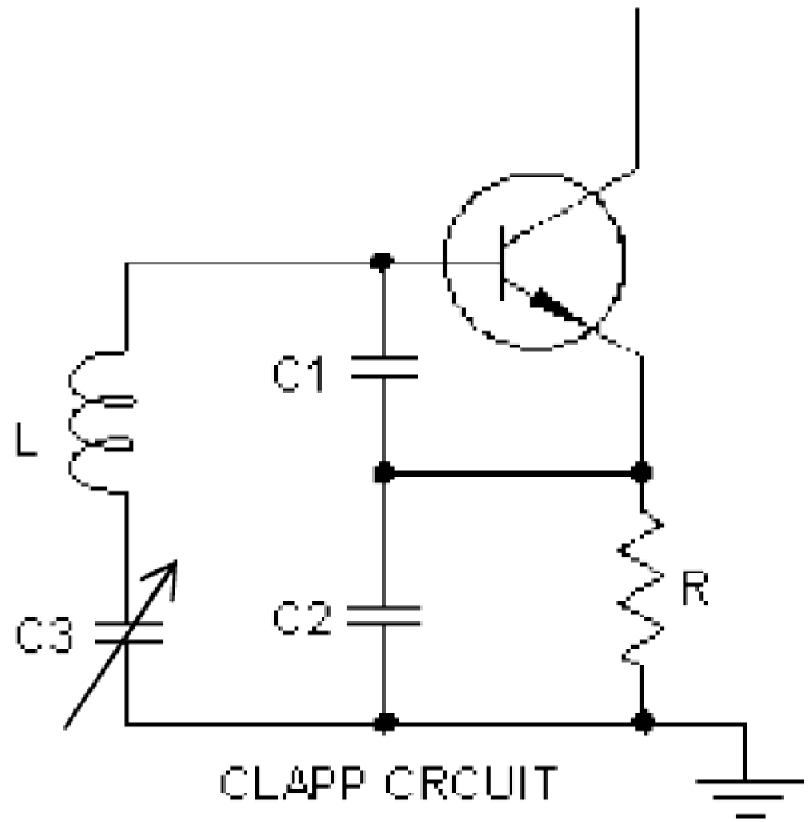
$|R_{NEG}| > R_{LOSS}$

- **Stable amplitude condition: $|R_{NEG}| = R_{LOSS}$ EXACTLY**
- **Frequency determined by LC network**
- **Startup: random noise; begin with $|R_{NEG}| > R_{LOSS}$**
- **Amplitude grows; soft clip gives average $|R_{NEG}| = R_{LOSS}$**

Clapp oscillator

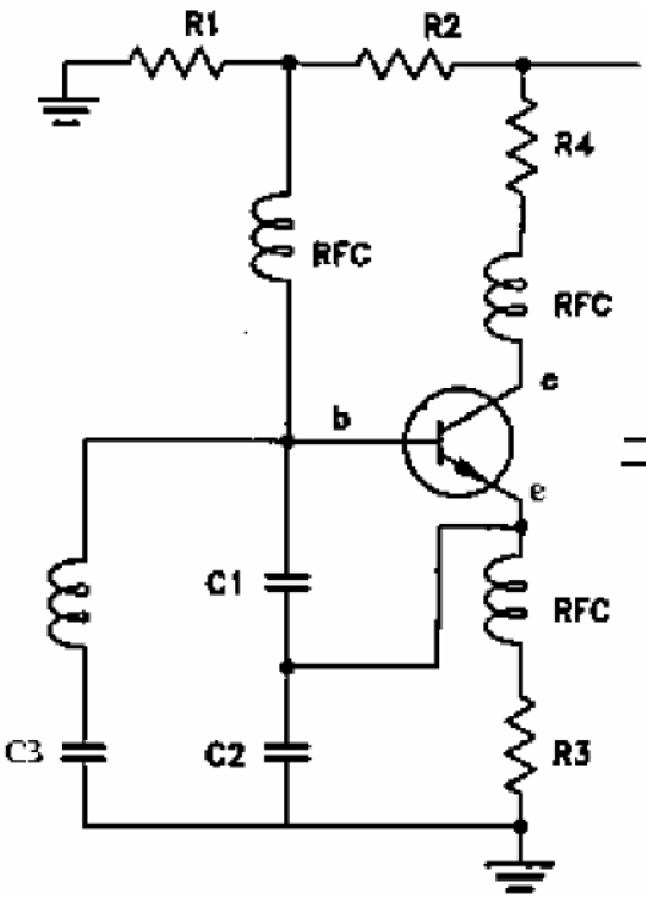
$$f_{OSC} = \frac{1}{2\pi\sqrt{LC_{eq}}}$$

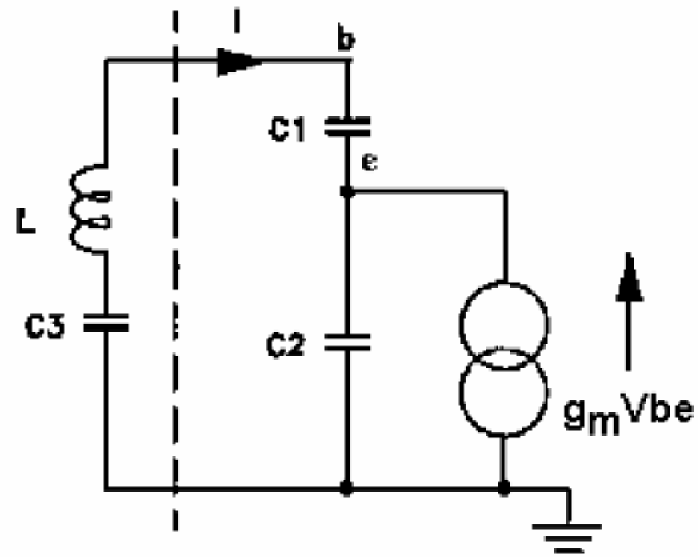
$$C_{eq} = \frac{1}{\left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}\right)}$$



- **L, C1-C2-C3 set oscillation frequency** f_{OSC}

Clapp oscillator

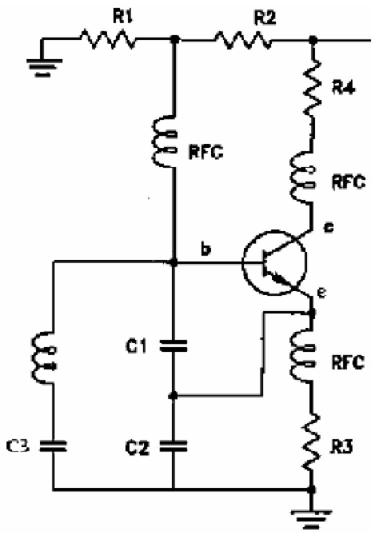




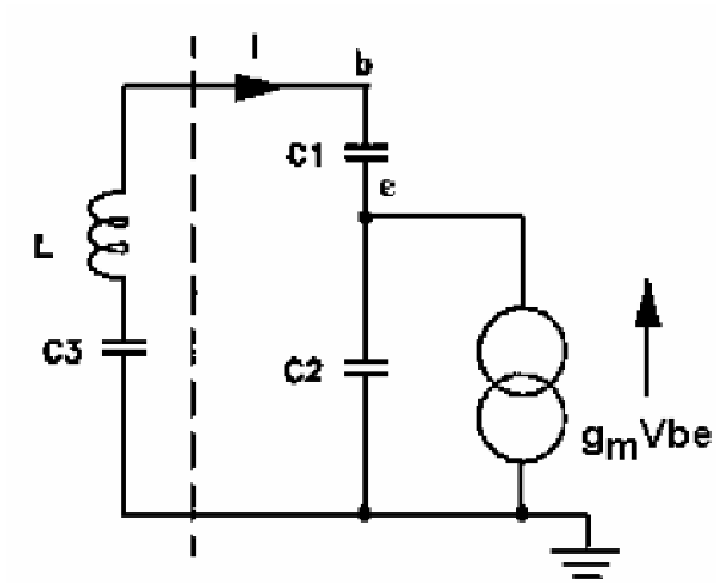
- **Circuit configuration**
- **Equivalent circuit**

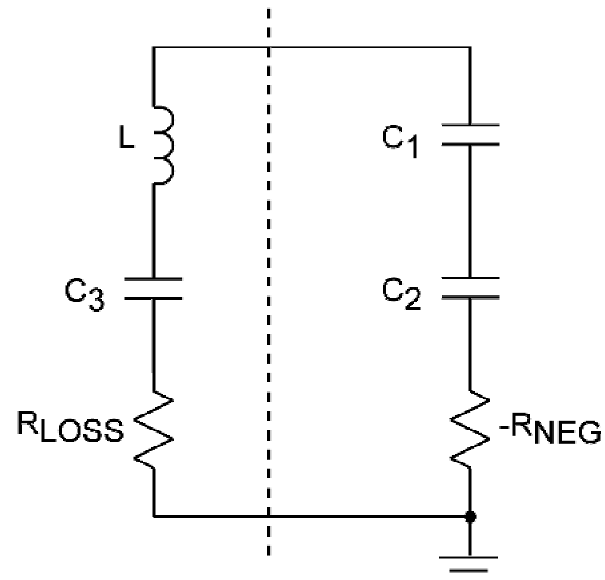
MiniCircuits AN95-007, “Understanding Oscillator Concepts”

Clapp oscillator



$$Z_{eq} = \frac{1}{j\omega C_1} + \frac{1}{j\omega C_2} - \frac{g_m}{\omega^2 C_1 C_2}$$

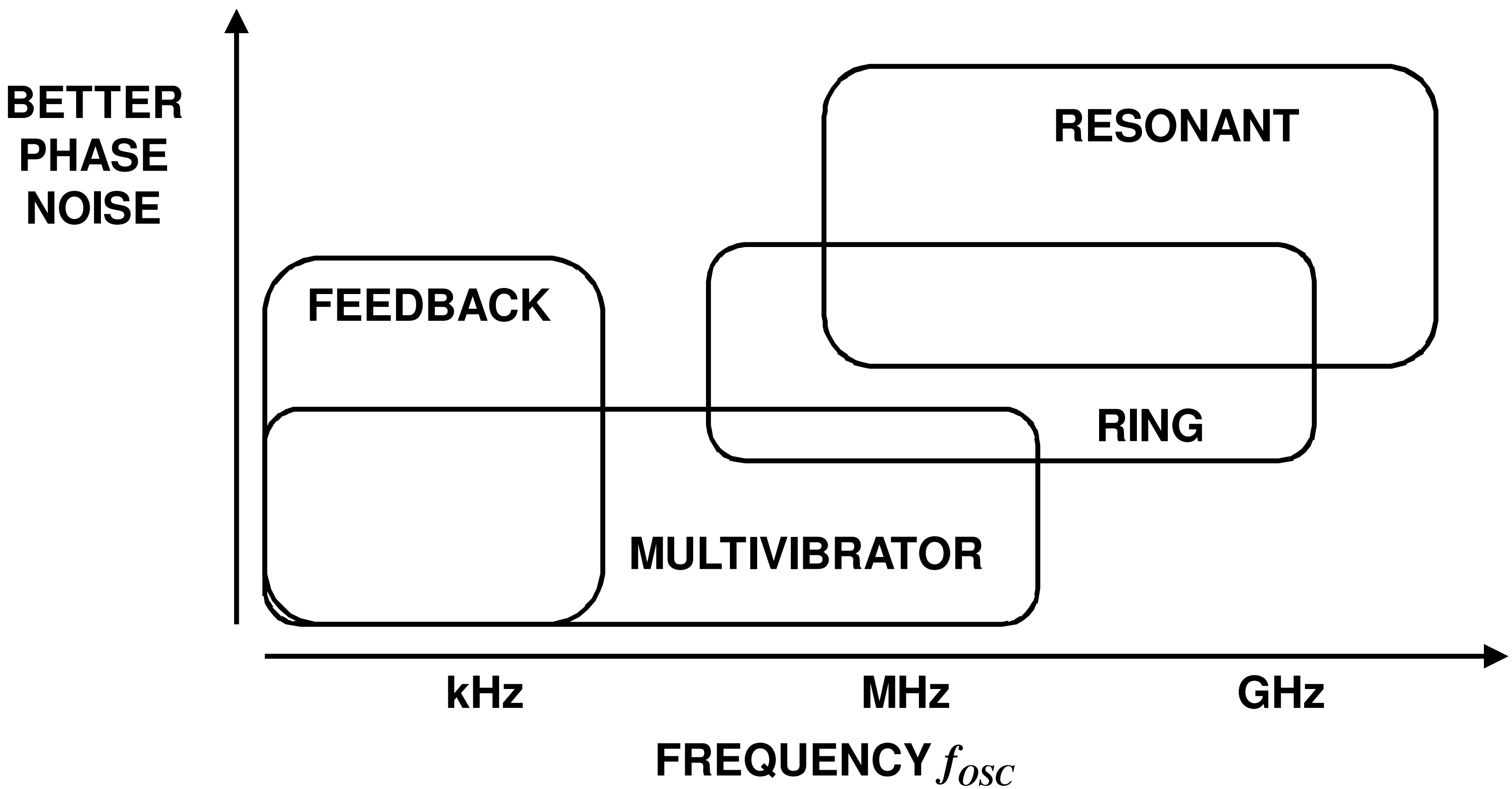




- **Frequency: Determined by L, C1, C2, C3**
- **Amplitude: Grows until limited by g_m soft clipping**
- **Startup: Choose C1, C2 feedback for $| R_{NEG} | > R_{LOSS}$**

Oscillator Summary

- **Typical performance of oscillator architectures:**



Overview

- Functional Block Concept
- Oscillator Review
- **Basic Performance Metrics**
  - **Frequency Range**
  - **Tuning Range**
- Methods of Tuning
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Basic Performance Metrics

VOLTAGE CONTROLLED OSCILLATORS 50 Ω

12.5 MHz to 3 GHz

MOS Case CZ682 | ROS Case CK605, CK1113, CK829 | JTOS Case BK377 | JCOS Case BG419

MODEL PREFIX	FREQUENCY (MHz)		POWER OUTPUT (dBm)	TUNE VOLTAGE (V)		PHASE NOISE (dBc/Hz) SSB@ offset frequencies: Typ.				PULLING (MHz) pk-pk @12 dBr	PUSHING (MHz/V)	TUNING SENSITIVITY (MHz/V)	HARMONICS (dBc)		3dB MOD. BANDWIDTH (kHz)	POWER SUPPLY Voltage (V)	POWER SUPPLY Current (mA)
	Min.	Max.	Typ.	Min.	Max.	1 kHz	10 kHz	100 kHz	1 MHz	Typ.	Typ.	Typ.	Typ.	Max.	Typ.	Nom.	Max.
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JTOS-50	25	47	+8.5	1.0	15.0	-88	-108	-127	-147	0.06	0.04	2.0-2.6	-19	-12	50	12.0	20
JTOS-75	37.5	75	+8.0	1.0	16.0	-89	-110	-130	-140	0.15	0.11	2.8-4.0	-27	-20	125	12.0	20
JTOS-100	50	100	+8.3	1.0	16.0	-83	-108	-128	-140	0.6	0.2	3.7-4.8	-35	-20	100	12.0	18
JTOS-150	75	150	+9.5	1.0	16.0	-82	-106	-127	-147	0.8	0.3	5.8-6.7	-23	-17	112	12.0	20
JTOS-200	100	200	+10.0	1.0	16.0	-84	-105	-124	-145	1.0	0.2	6-10	-25	-20	110	12.0	20
JTOS-300	150	280	+9.0	1.0	16.0	-82	-102	-122	-142	1.0	0.2	9-14	-28	-20	120	12.0	20
JTOS-400	200	380	+9.0	1.0	16.0	-82	-102	-122	-142	1.4	0.4	10.5-17.1	-25	-20	130	12.0	20
JTOS-535	300	525	+9.5	1.0	16.0	-75	-97	-117	-137	2.0	0.5	10-24	-28	-20	115	12.0	20
JTOS-765	485	765	+8.0	1.0	16.0	-75	-98	-118	-138	2.0	0.5	20-30	-30	-20	100	12.0	20
JTOS-850VW	400	850	+6.0	0.5	18.0	-74	-96	-116	-136	6.0	1.5	15-80	-20	—	185	5.0	20
JTOS-1000W	500	1000	+7.0	1.0	18.0	-73	-94	-114	-134	5.0	1.0	30-40	-26	-20	100	12.0	25

Mini-Circuits®

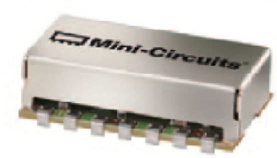
Basic Performance Metrics

Surface Mount

Voltage Controlled Oscillator JTOS-1000W+

Wide Band 500 to 1000 MHz

Features
- wide frequency range, 500 to 1000 MHz typ.
- 3 dB modulation bandwidth 100 kHz typ.
- octave, linear tuning
- low phase noise, -134 dBc/Hz at 1 MHz offset, typ.
- excellent harmonic suppression, -26 dBc typ.
- aqueous washable



CASE STYLE: BK377
PRICE: $21.95 ea. QTY (5-49)

Applications
- test instruments-signal generators
- wideband frequency synthesizers
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+RoHS Compliant
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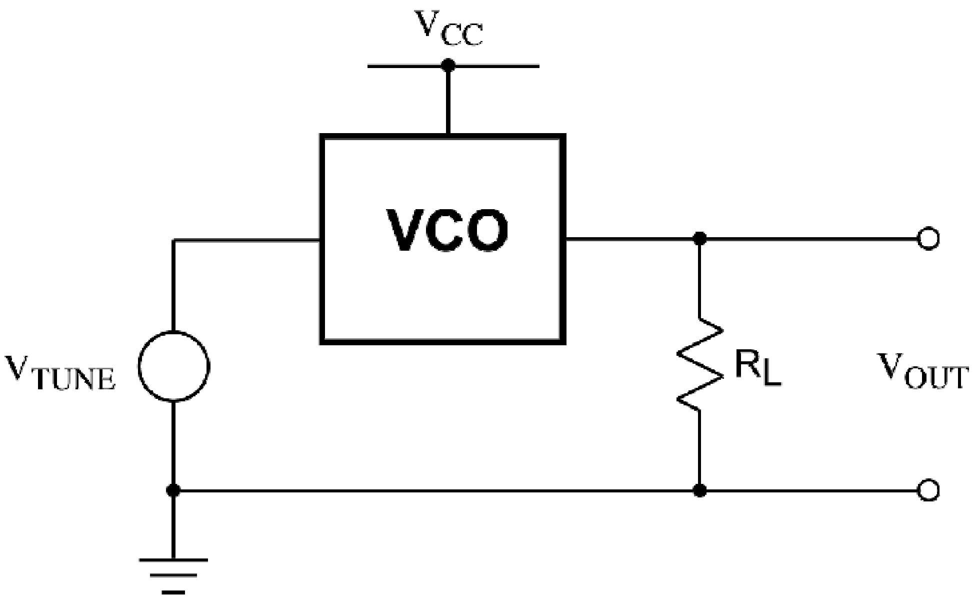
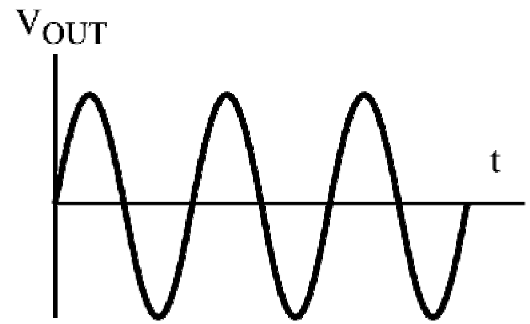
Electrical Specifications

FREQUENCY (MHz)		POWER OUTPUT (dBm)	TUNING VOLTAGE (V)		PHASE NOISE (dBc/Hz) SSB at offset frequencies: Typ.				PULLING pk-pk @ 12 dBr (MHz)	PUSHING (MHz/V)	TUNING SENSITIVITY (MHz/V)	HARMONICS (dBc)		3 dB MODULATION BANDWIDTH (MHz)	DC OPERATING POWER	
Min.	Max.	Typ.	Min.	Max.	1 kHz	10 kHz	100 kHz	1 MHz	Typ.	Typ.	Typ.	Typ.	Max.	Typ.	Vcc (volts)	Current (mA) Max.
500	1000	+7.0	1.0	18	-73	-94	-114	-134	5.0	1.0	30-40	-26	-20	0.1	12	25

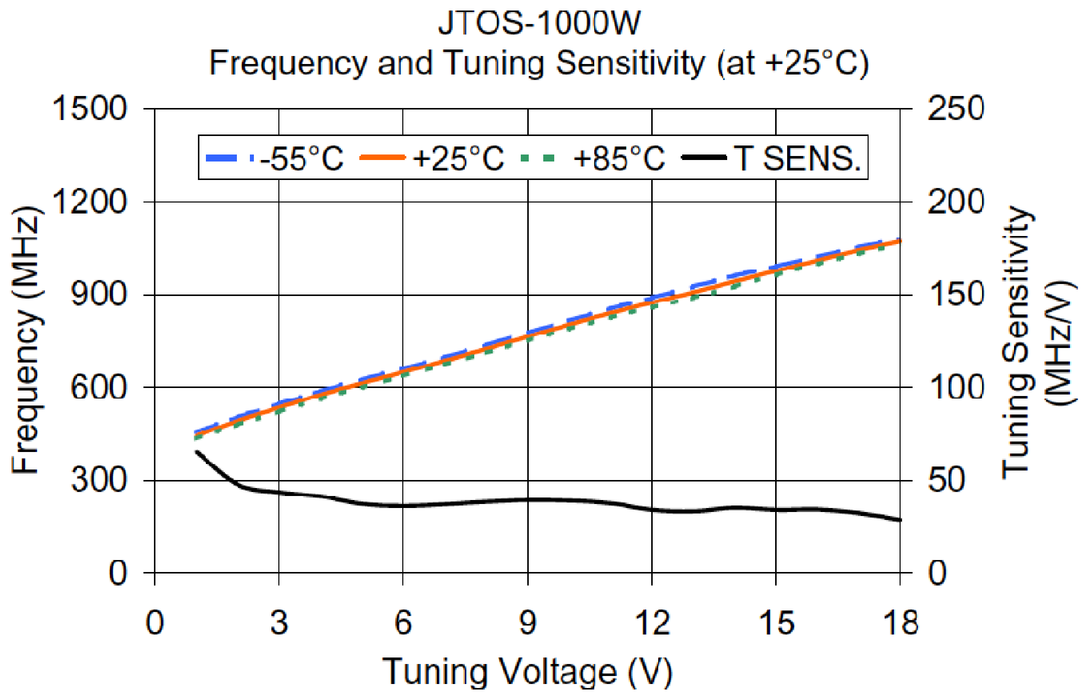
Basic Performance Metrics





- Supply: DC operating power
- Output
  - Sine: output power dBm into 50Ω
  - Square: compatible logic
- Frequency Range
- Tuning Voltage Range

Frequency Range



V TUNE	TUNING SENS. (MHz/V)	FREQUENCY (MHz) -55°C	FREQUENCY (MHz) +25°C	FREQUENCY (MHz) +85°C
1.00	65.31	455.40	443.44	433.76
2.00	47.64	503.88	491.08	480.00
3.00	43.38	546.43	534.46	521.76
4.00	41.23	587.53	575.68	562.24
5.00	37.18	624.47	612.87	600.23
6.00	36.00	660.47	648.87	636.80
7.00	36.98	697.54	685.84	673.93
8.00	38.32	736.41	724.17	711.94
9.00	39.19	775.71	763.36	750.82
10.00	38.93	815.33	802.29	789.02
11.00	37.42	854.60	839.71	825.08
12.00	33.97	889.31	873.67	857.98
13.00	33.20	925.48	906.87	889.55
14.00	35.13	960.60	942.00	925.73
15.00	33.97	991.30	975.97	963.00
16.00	34.17	1022.17	1010.14	999.00
17.00	32.21	1052.63	1042.35	1031.78
18.00	28.65	1081.03	1070.99	1060.58

- **Output frequency over tuning voltage range**
- **Caution: Temperature sensitivity**

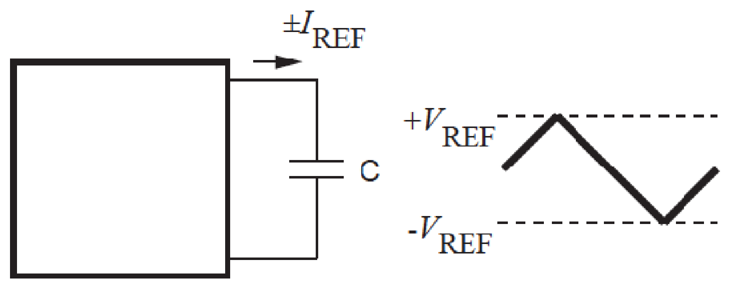
Overview

- Functional Block Concept
- Oscillator Review
- Basic Performance Metrics
- **Methods of Tuning**
- Advanced Performance Metrics
- Conclusion

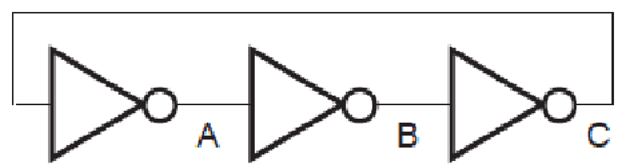
VCOs / Methods of Tuning

- **Require electrical control of some parameter determining frequency:**

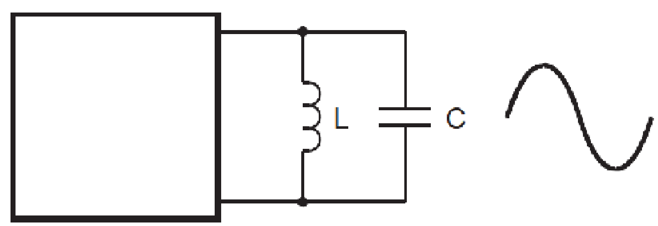
- **Multivibrator**
  - Charge / discharge current



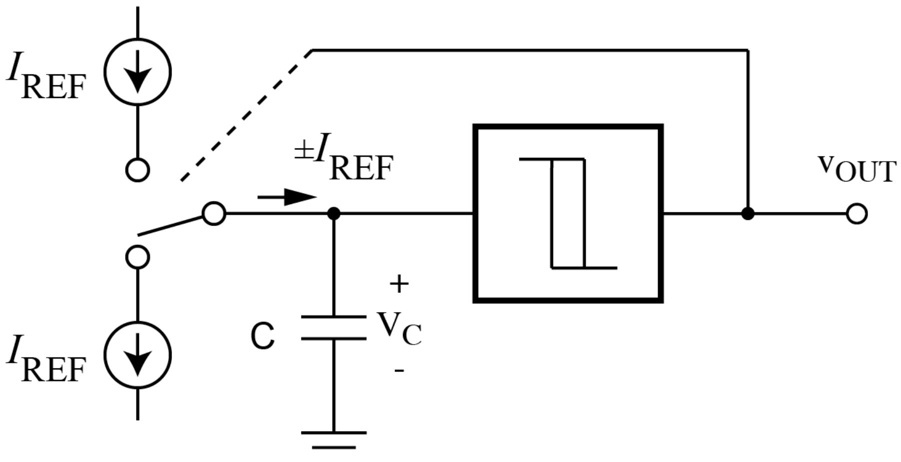
- **Ring Oscillator**
  - Gate delay



- **Resonant**
  - Voltage control of capacitance in LC (varactor)



Example: Tuning Multivibrator



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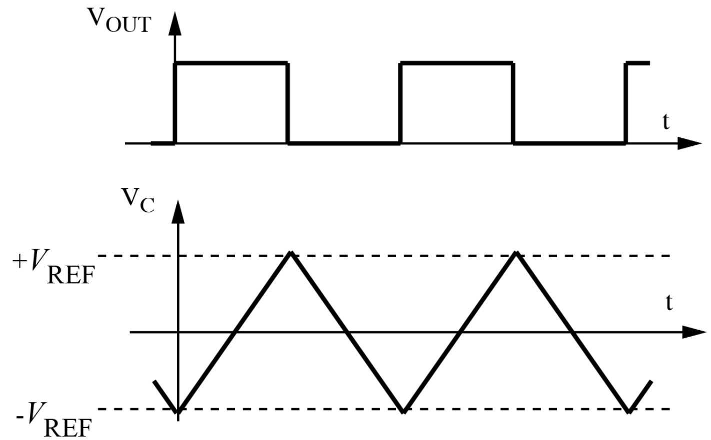


- Frequency: Controlled by I_{REF}, C, V_{REF} thresholds

$$f_{OSC} = \frac{I_{REF}}{4CV_{REF}}$$

- Use linear transconductance G_M to develop I_{REF} from V_{TUNE}

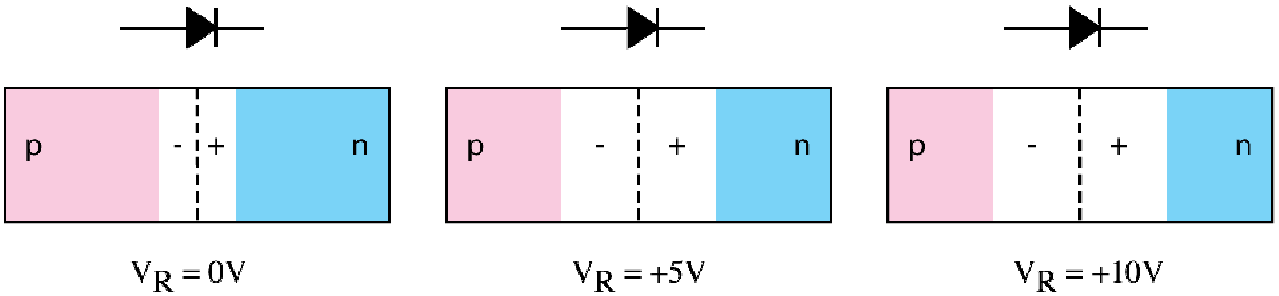
$$I_{REF} = G_M V_{TUNE}$$

$$f_{OSC} = \left(\frac{G_M}{4CV_{REF}}\right) V_{TUNE}$$

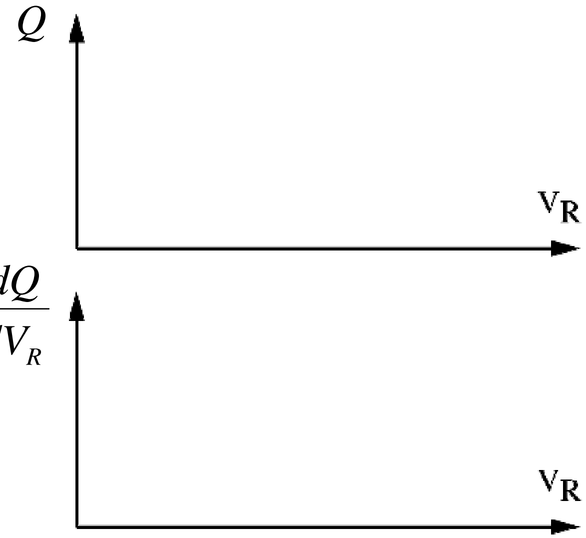
\+ Very linear $V_{TUNE} - f_{OSC}$ characteristic

\- But: poor phase noise; f_{OSC} limited to MHz range

Tuning LC Resonator: Varactor



$$C_j = \frac{dQ}{dV_R}$$

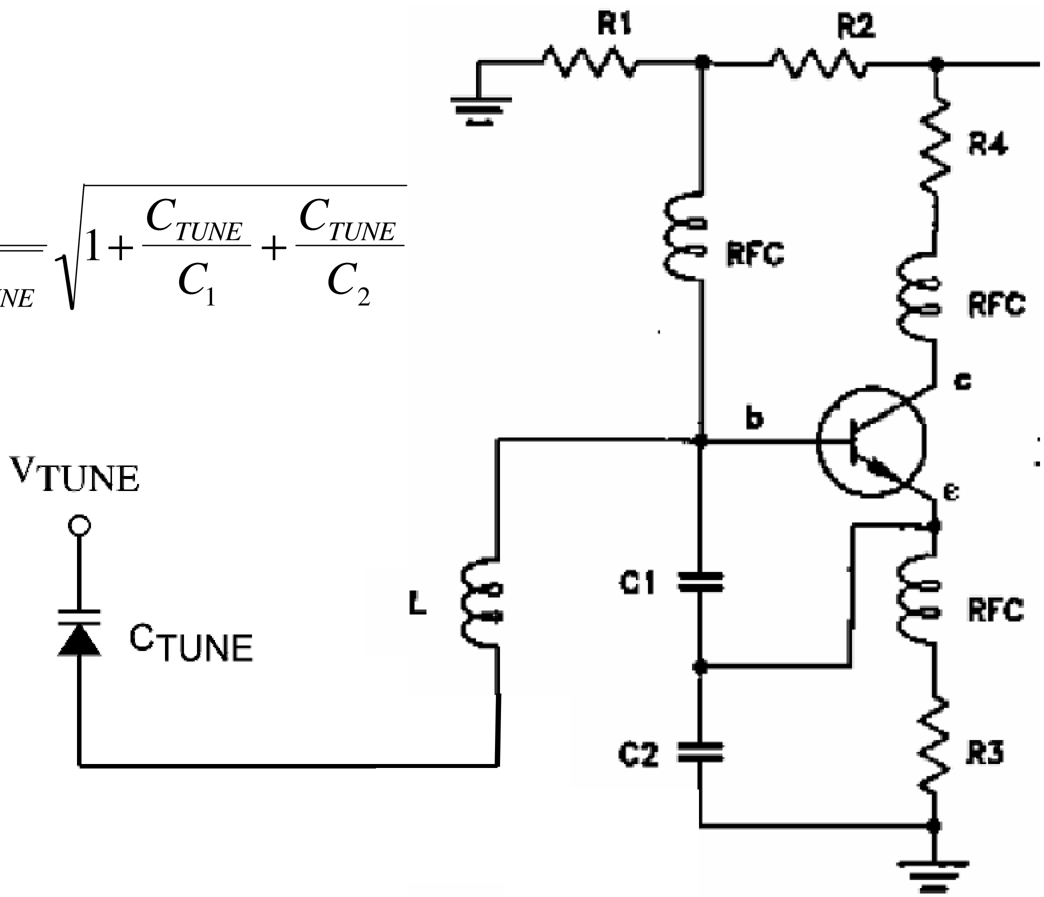


$$C_j = \frac{C_{j0}}{\left(1 + \frac{V_R}{V_{bi}}\right)^m}$$

- **Q-V characteristic of pn junction**
- **Use reverse bias diode for C in resonator**

Example: Clapp oscillator

$$f_{OSC} = \frac{1}{2\pi\sqrt{LC_{TUNE}}}\sqrt{1+\frac{C_{TUNE}}{C_1}+\frac{C_{TUNE}}{C_2}}$$



- Tuning range f_{MIN}, f_{MAX} set by C_{TUNE} maximum, minimum
- Want C_1, C_2 > C_{TUNE} for wider tuning range

Overview

- Functional Block Concept
- Oscillator Review
- Basic Performance Metrics
- Methods of Tuning
- **Advanced Performance Metrics**
  - **Tuning Sensitivity**
  - **Phase Noise**
  - **Supply Pushing**
  - **Load Pulling**
- Conclusion

Advanced Performance Metrics

VOLTAGE CONTROLLED OSCILLATORS 50 Ω

12.5 MHz to 3 GHz

MOS Case CZ682 | ROS Case CK605, CK1113, CK829 | JTOS Case BK377 | JCOS Case BG419

MODEL PREFIX	FREQUENCY (MHz)		POWER OUTPUT (dBm)	TUNE VOLTAGE (V)		PHASE NOISE (dBc/Hz) SSB@ offset frequencies: Typ.				PULLING (MHz) pk-pk @12 dBr	PUSHING (MHz/V)	TUNING SENSITIVITY (MHz/V)	HARMONICS (dBc)		3dB MOD. BANDWIDTH (kHz)	POWER SUPPLY	
	Min.	Max.	Typ.	Min.	Max.	1 kHz	10 kHz	100 kHz	1 MHz	Typ.	Typ.	Typ.	Typ.	Max.	Typ.	Voltage (V) Nom.	Current (mA) Max.
LINEAR TUNING ***Wideband***																	
JCOS-175LN	125	175	+3.7	1.0	17.0	-95	-118	-138	-158	0.08	0.05	3-5	-25	-20	2900	12.0	20
JCOS-820BLN	807	832	+3.0	1.0	14.0	-88	-112	-132	-151	0.4	0.4	6.0	-24	-20	2000	10.0	25
JCOS-820WLN	780	860	+9.0	0.0	20.0	-90	-112	-132	-150	4.5	0.3	8.0	-13	-8	2000	9.0	25
JCOS-1100LN	1079	1114	+8.5	0.0	20.0	-88	-110	-130	-150	7.5	0.5	4.5	-15	-10	2000	8.0	25
JTOS-25	12.5	25	+8.0	1.0	11.0	-95	-115	-135	-155	0.03	0.02	1.0-4.0	-26	-13	130	12.0	20
JTOS-50	25	47	+8.5	1.0	15.0	-88	-108	-127	-147	0.06	0.04	2.0-2.6	-19	-12	50	12.0	20
JTOS-75	37.5	75	+8.0	1.0	16.0	-89	-110	-130	-140	0.15	0.11	2.8-4.0	-27	-20	125	12.0	20
JTOS-100	50	100	+8.3	1.0	16.0	-83	-108	-128	-140	0.6	0.2	3.7-4.8	-35	-20	100	12.0	18
JTOS-150	75	150	+9.5	1.0	16.0	-82	-106	-127	-147	0.8	0.3	5.8-6.7	-23	-17	112	12.0	20
JTOS-200	100	200	+10.0	1.0	16.0	-84	-105	-124	-145	1.0	0.2	6-10	-25	-20	110	12.0	20
JTOS-300	150	280	+9.0	1.0	16.0	-82	-102	-122	-142	1.0	0.2	9-14	-28	-20	120	12.0	20
JTOS-400	200	380	+9.0	1.0	16.0	-82	-102	-122	-142	1.4	0.4	10.5-17.1	-25	-20	130	12.0	20
JTOS-535	300	525	+9.5	1.0	16.0	-75	-97	-117	-137	2.0	0.5	10-24	-28	-20	115	12.0	20
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JTOS-850VW	400	850	+6.0	0.5	18.0	-74	-96	-116	-136	6.0	1.5	15-80	-20	—	185	5.0	20
JTOS-1000W	500	1000	+7.0	1.0	18.0	-73	-94	-114	-134	5.0	1.0	30-40	-26	-20	100	12.0	25

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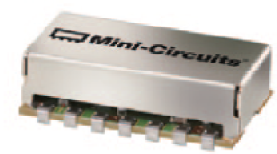
Tuning Sensitivity

Surface Mount

Voltage Controlled Oscillator JTOS-1000W+

Wide Band 500 to 1000 MHz

Features
- wide frequency range, 500 to 1000 MHz typ.
- 3 dB modulation bandwidth 100 kHz typ.
- octave, linear tuning
- low phase noise, -134 dBc/Hz at 1 MHz offset, typ.
- excellent harmonic suppression, -26 dBc typ.
- aqueous washable



CASE STYLE: BK377
PRICE: $21.95 ea. QTY (5-49)

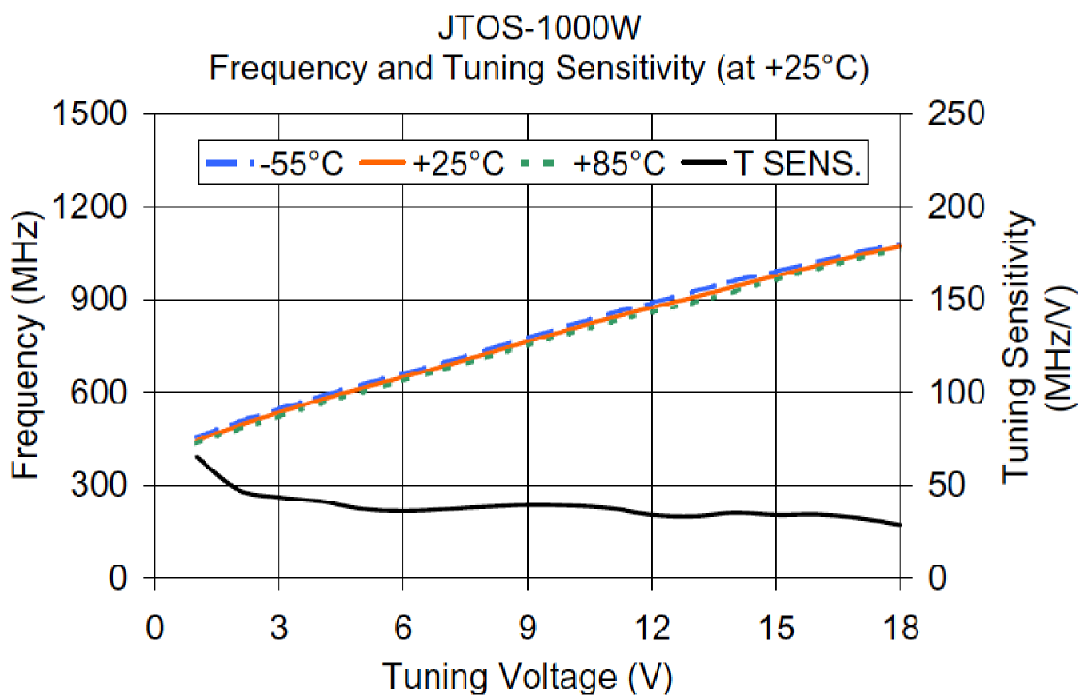
Applications
- test instruments-signal generators
- wideband frequency synthesizers
- agile communications systems
- catv distribution and set-top convertors
- cellular up and down converters
- digital cordless phones

+RoHS Compliant
The +Suffix identifies RoHS Compliance. See our web site for RoHS Compliance methodologies and qualifications

Electrical Specifications

FREQUENCY (MHz)		POWER OUTPUT (dBm)	TUNING VOLTAGE (V)		PHASE NOISE (dBc/Hz) SSB at offset frequencies: Typ.				PULLING pk-pk @ 12 dBr (MHz)	PUSHING (MHz/V)	TUNING SENSITIVITY (MHz/V)	HARMONICS (dBc)		3 dB MODULATION BANDWIDTH (MHz)	DC OPERATING POWER	
Min.	Max.	Typ.	Min.	Max.	1 kHz	10 kHz	100 kHz	1 MHz	Typ.	Typ.	Typ.	Typ.	Max.	Typ.	Vcc (volts)	Current (mA) Max.
500	1000	+7.0	1.0	18	-73	-94	-114	-134	5.0	1.0	30-40	-26	-20	0.1	12	25

Frequency Range



V TUNE	TUNING SENS. (MHz/V)	FREQUENCY (MHz) -55°C	+25°C	+85°C
1.00	65.31	455.40	443.44	433.76
2.00	47.64	503.88	491.08	480.00
3.00	43.38	546.43	534.46	521.76
4.00	41.23	587.53	575.68	562.24
5.00	37.18	624.47	612.87	600.23
6.00	36.00	660.47	648.87	636.80
7.00	36.98	697.54	685.84	673.93
8.00	38.32	736.41	724.17	711.94
9.00	39.19	775.71	763.36	750.82
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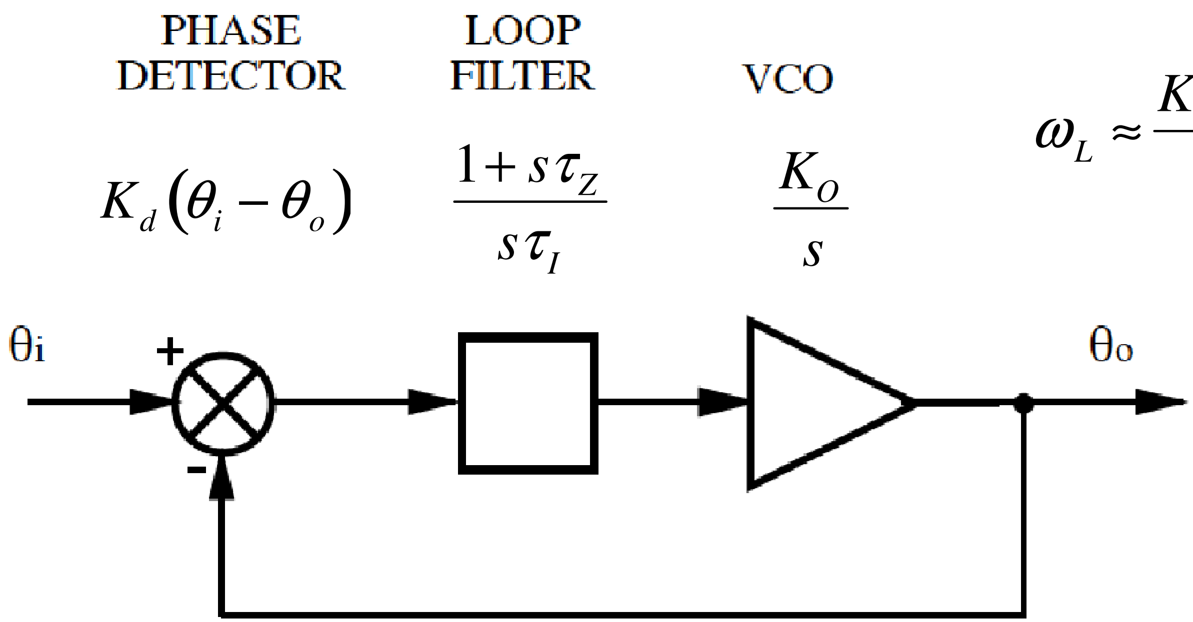
15.00	33.97	991.30	975.97	963.00
16.00	34.17	1022.17	1010.14	999.00
17.00	32.21	1052.63	1042.35	1031.78
18.00	28.65	1081.03	1070.99	1060.58

- **Change in slope [MHz/V] over tuning voltage range**

Tuning Sensitivity



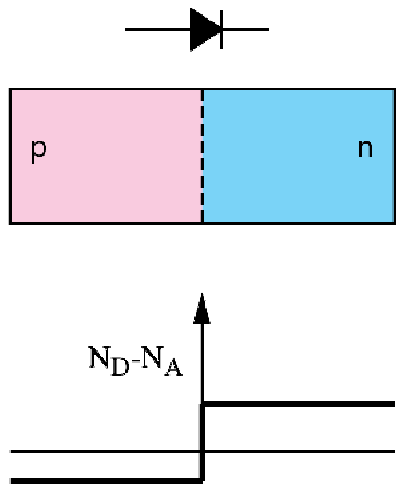
$$\omega_L \approx \frac{K_d K_O \tau_Z}{\tau_I}$$

Fig. 3.5. Phaselock loop as a control system.

- **Why do you care?**
  - **PLL: Tuning sensitivity K_O affects control parameters**
  - **Loop bandwidth ω_L (may not be critical)**
  - **Stability (critical!)**

Varactor Tuning

$$C_j = \frac{C_{j0}}{\left(1+\frac{V_{TUNE}}{V_{bi}}\right)^m}$$



$$f_{OSC} = \frac{1}{2\pi\sqrt{LC}}$$

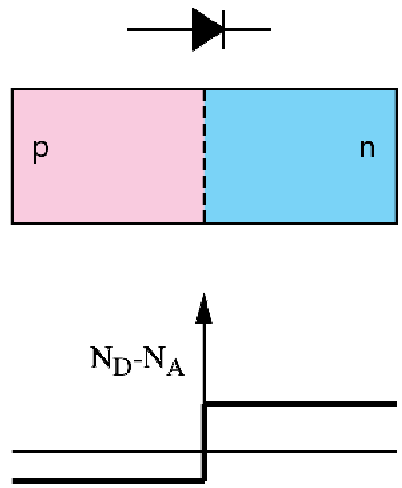
$$f_{OSC} \approx \frac{1}{2\pi\sqrt{LC_{j0}}}\left(\frac{V_{TUNE}}{V_{bi}}\right)^{m/2}$$

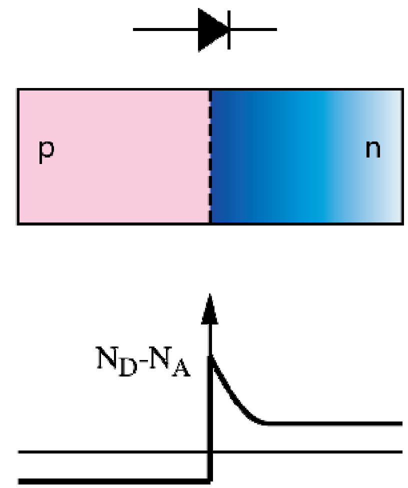
$$m = 1/2$$

- **Disadvantages of abrupt junction C-V characteristic (m=1/2)**
  - **Smaller tuning range**
  - **Inherently nonlinear $V_{TUNE} - f_{OSC}$ characteristic**

Hyperabrupt Junction Varactor

$$C_j = \frac{C_{j0}}{\left(1+\frac{V_{TUNE}}{V_{bi}}\right)^m}$$





$$f_{OSC} = \frac{1}{2\pi\sqrt{LC}}$$

$$f_{OSC} \approx \frac{1}{2\pi\sqrt{LC_{j0}}}\left(\frac{V_{TUNE}}{V_{bi}}\right)^{m/2}$$

$$m = 1/2$$

$$m \to 2$$

- **Hyperabrupt junction C-V characteristic (m ≈ 2)**
  - **+ Larger tuning range; more linear** $V_{TUNE} - f_{OSC}$
  - **- Disadvantage: Lower Q in resonator**

Phase Noise

Surface Mount

Voltage Controlled Oscillator JTOS-1000W+

Wide Band 500 to 1000 MHz

Features
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- 3 dB modulation bandwidth 100 kHz typ.
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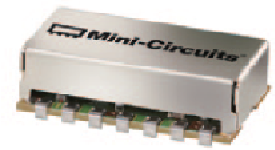

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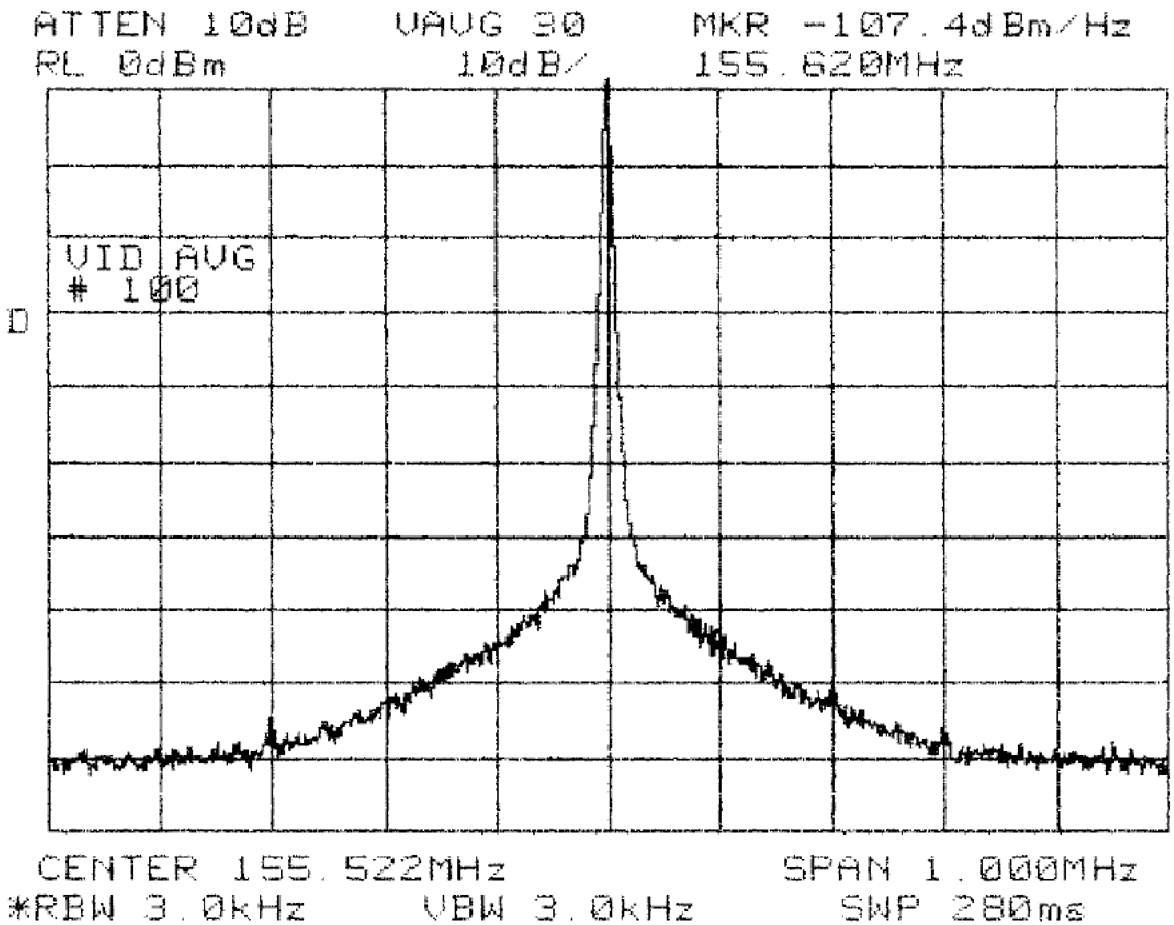
Min.	Max.	Typ.	Min.	Max.	1 kHz	10 kHz	100 kHz	1 MHz	Typ.	Typ.	Typ.	Typ.	Max.	Typ.	Vcc (volts)	Current (mA) Max.
500	1000	+7.0	1.0	18	-73	-94	-114	-134	5.0	1.0	30-40	-26	-20	0.1	12	25

Phase Noise



- **Power spectrum “close in” to carrier**

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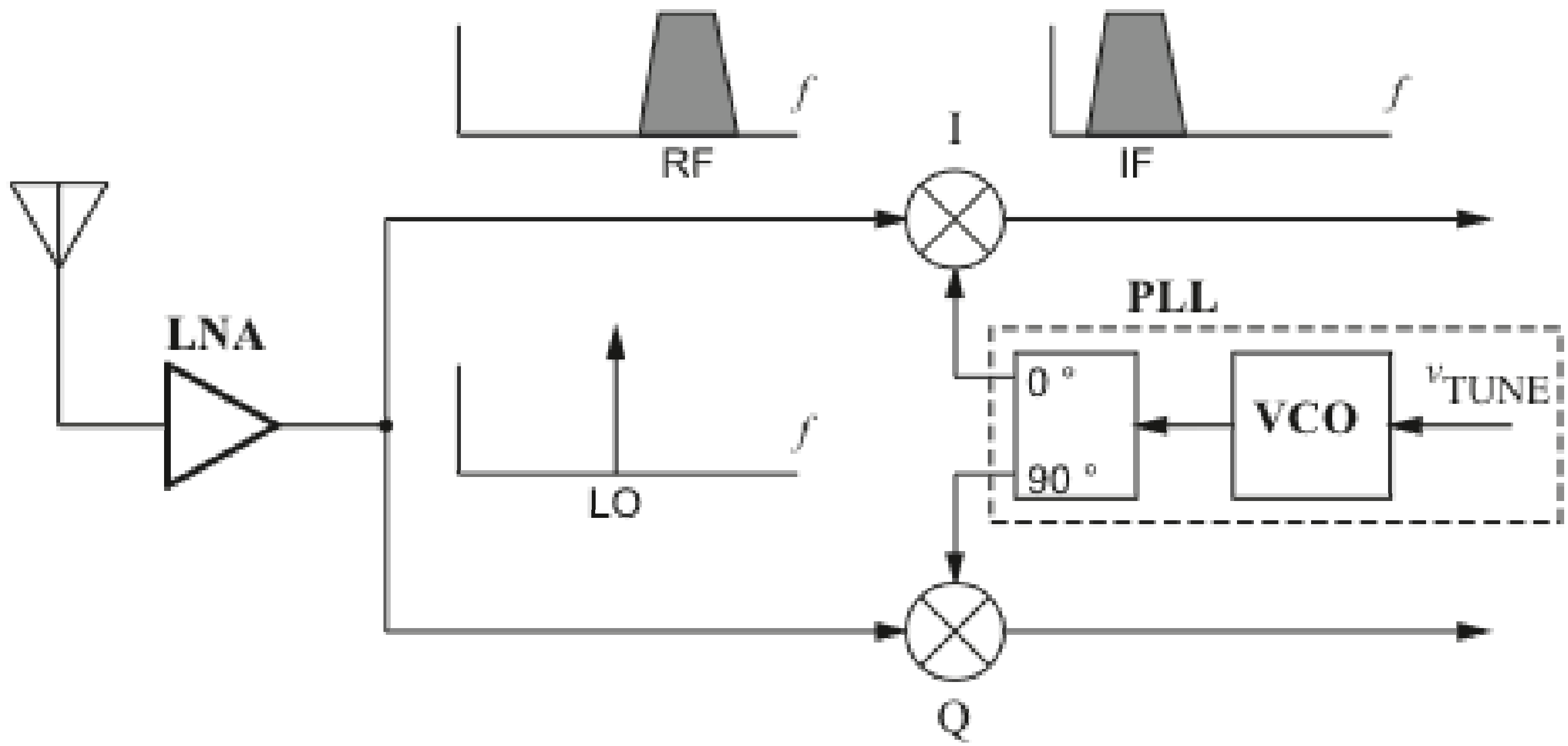
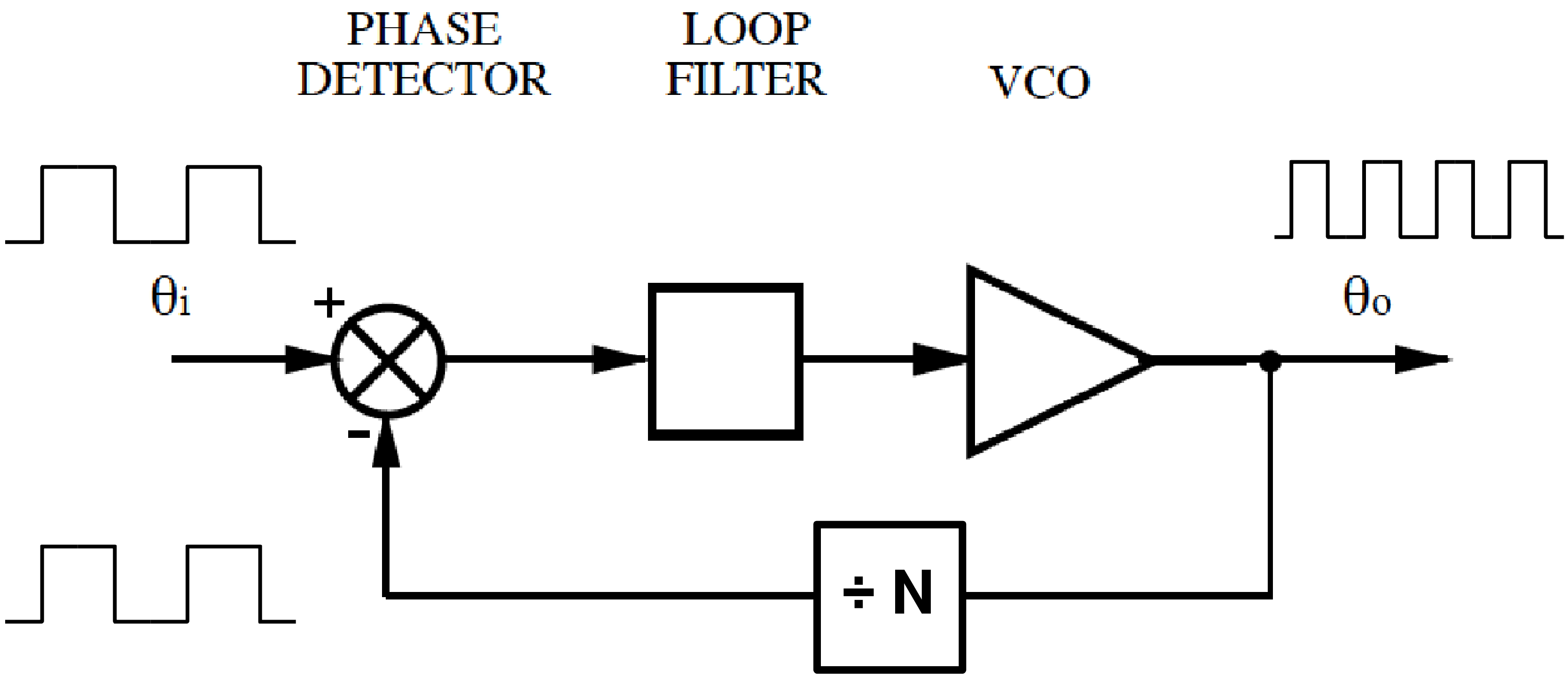
Phase Noise: RF System



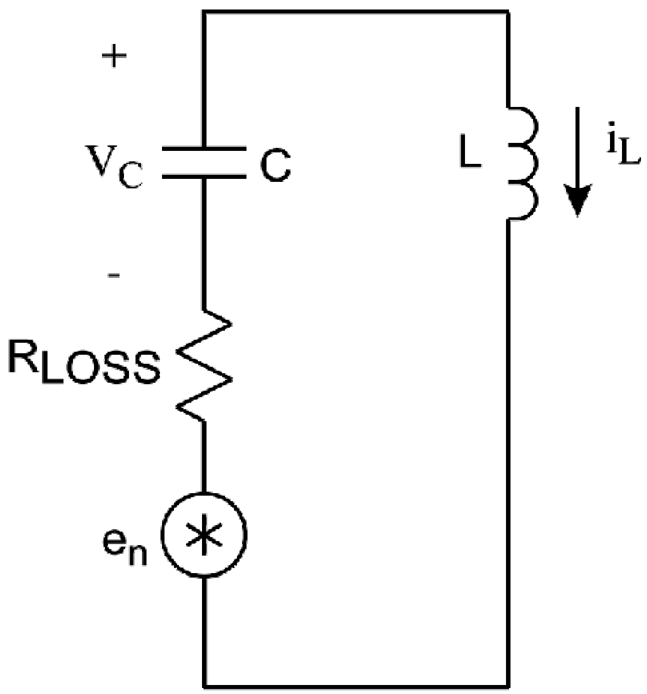
- **Mixers convolve LO spectrum with RF**
- **Phase noise "blurs" IF spectrum**

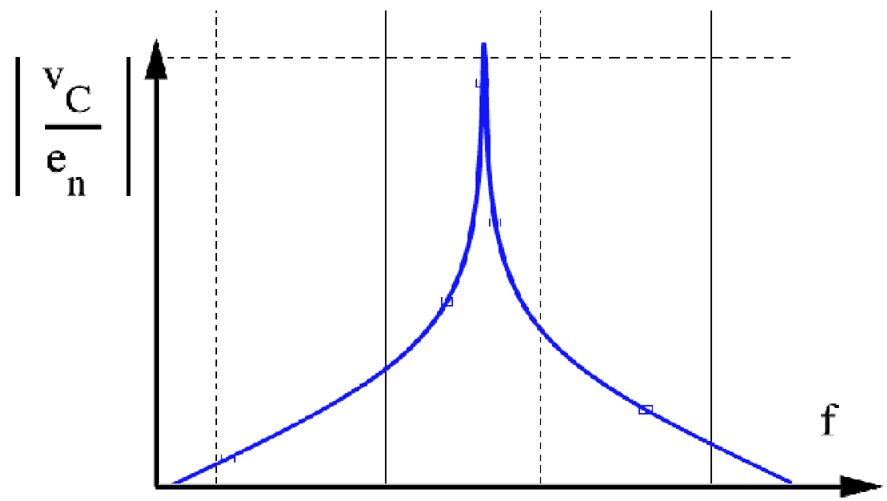
Phase Noise: Digital System



- Time domain jitter on synthesized output clock
- Decreases timing margin for system using clock

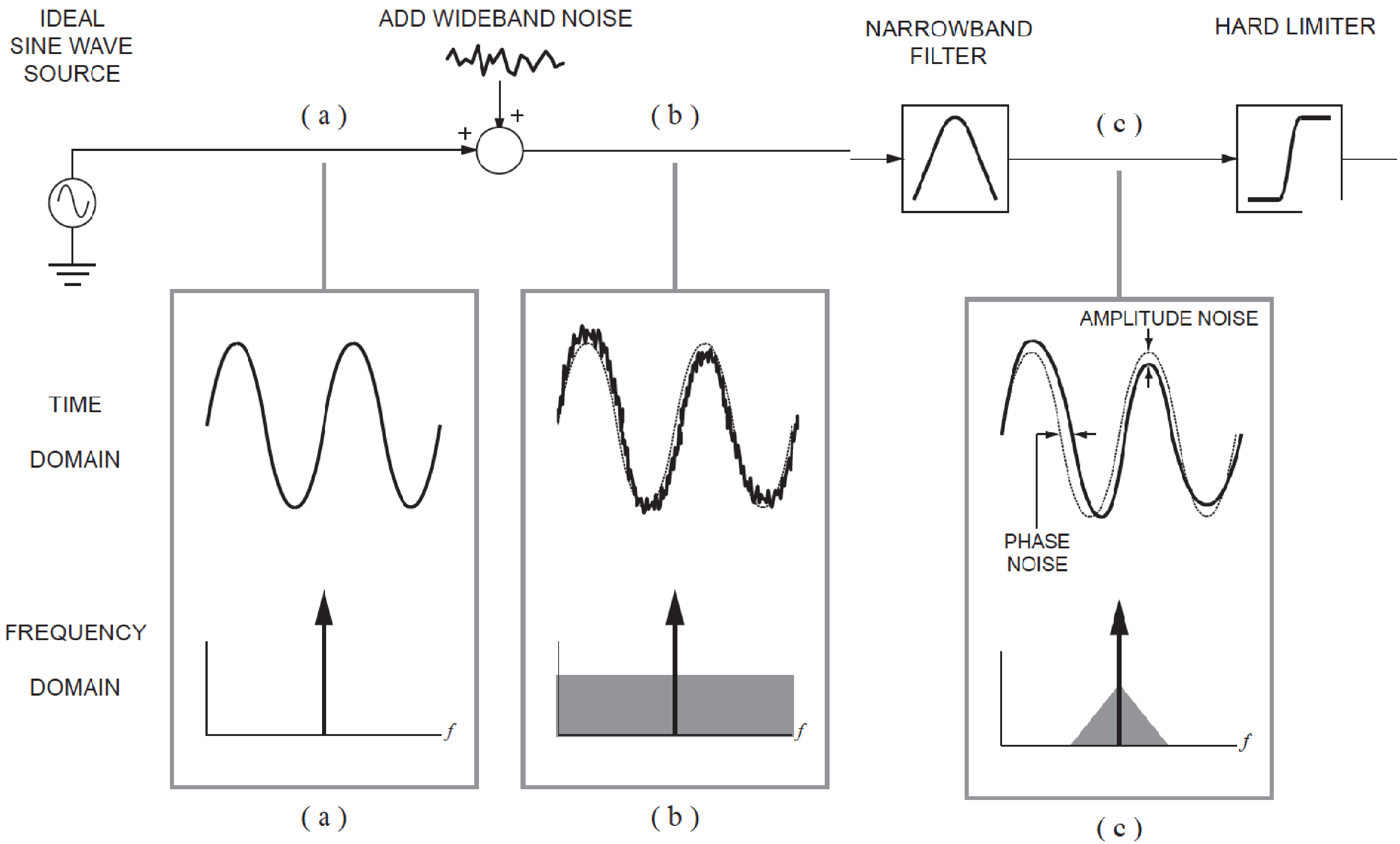
Shape of Phase Noise Spectrum



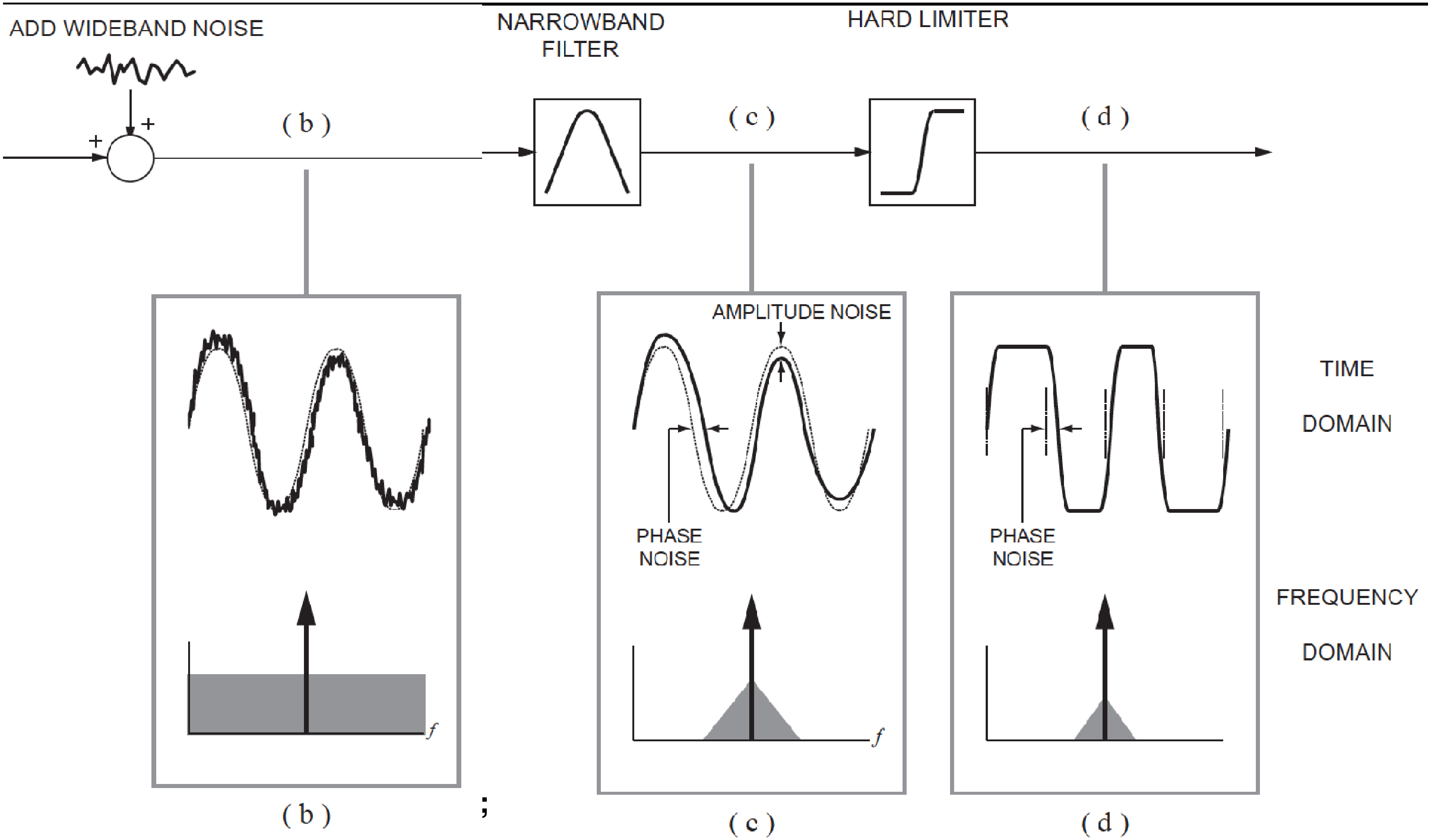


- LC filters noise into narrow band near fundamental
- High Q resonator preferred to minimize noise

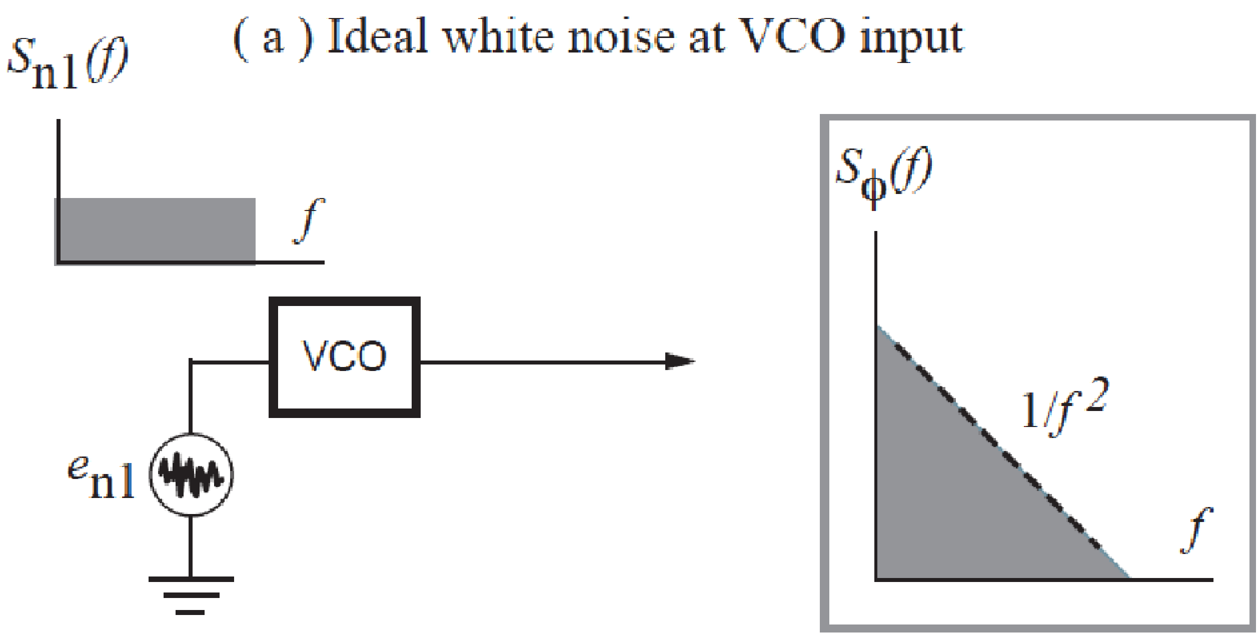
Phase Noise: Intuitive view



Phase Noise: Intuitive view



Phase Noise Description



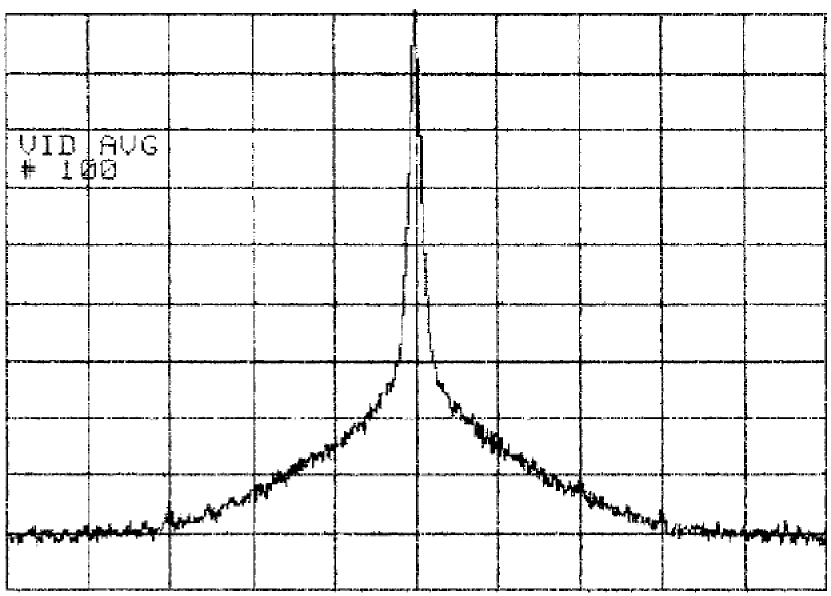
- Symmetric; look at single sided representation
- Normalized to carrier: dBc
- At different offset frequencies from carrier
- White frequency noise: phase noise with -20dB/decade slope
- Other noise processes change slope; 1/f noise gives -30dB/decade

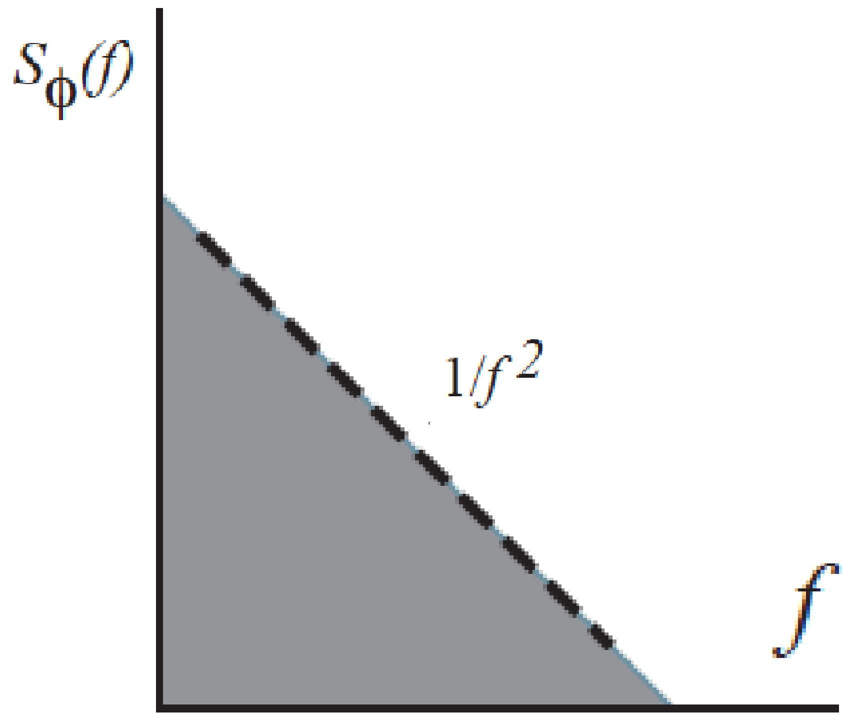
Phase Noise Specification

Surface Mount

Voltage Controlled Oscillator

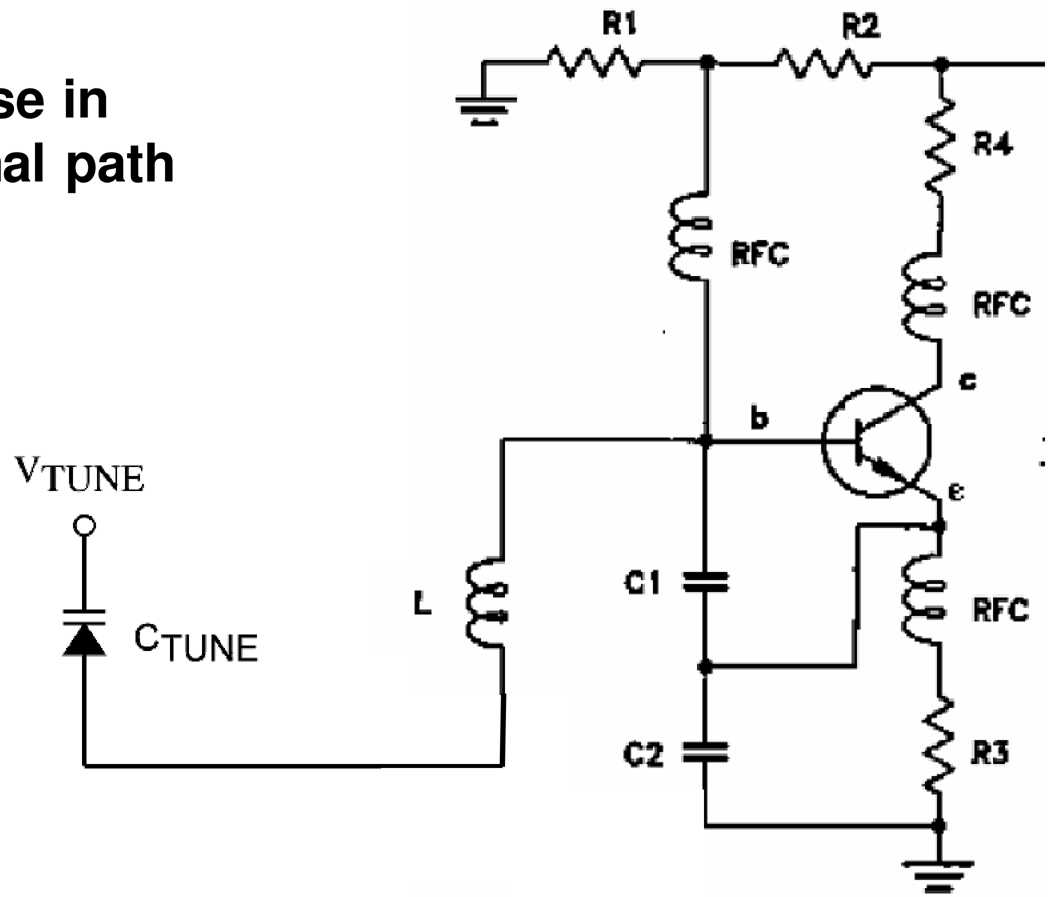
PHASE NOISE (dBc/Hz) SSB at offset frequencies: Typ.			
1 kHz	10 kHz	100 kHz	1 MHz
-73	-94	-114	-134





Sources of Phase Noise

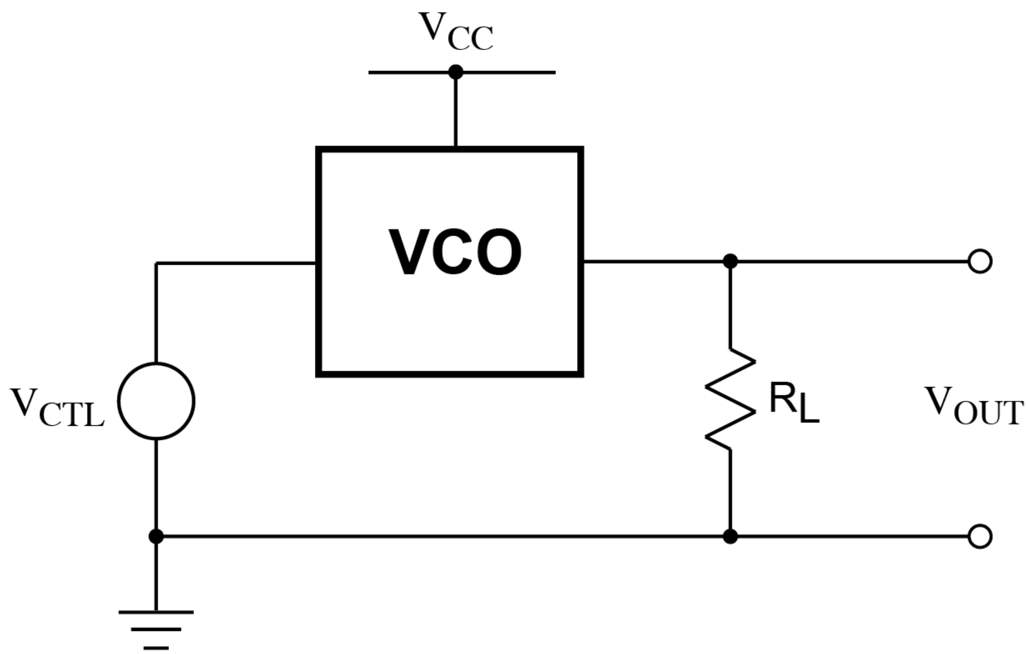
White noise in V_{TUNE} signal path



Noise of active devices

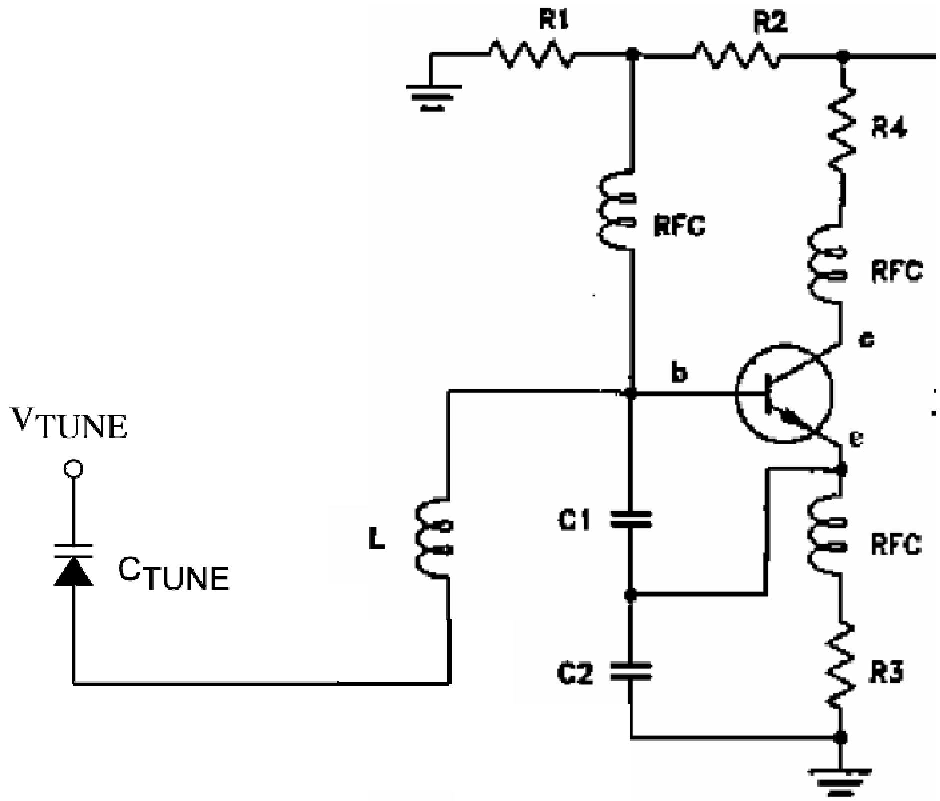
Thermal noise: Losses in resonator, series R of varactor

Supply / Load Sensitivity



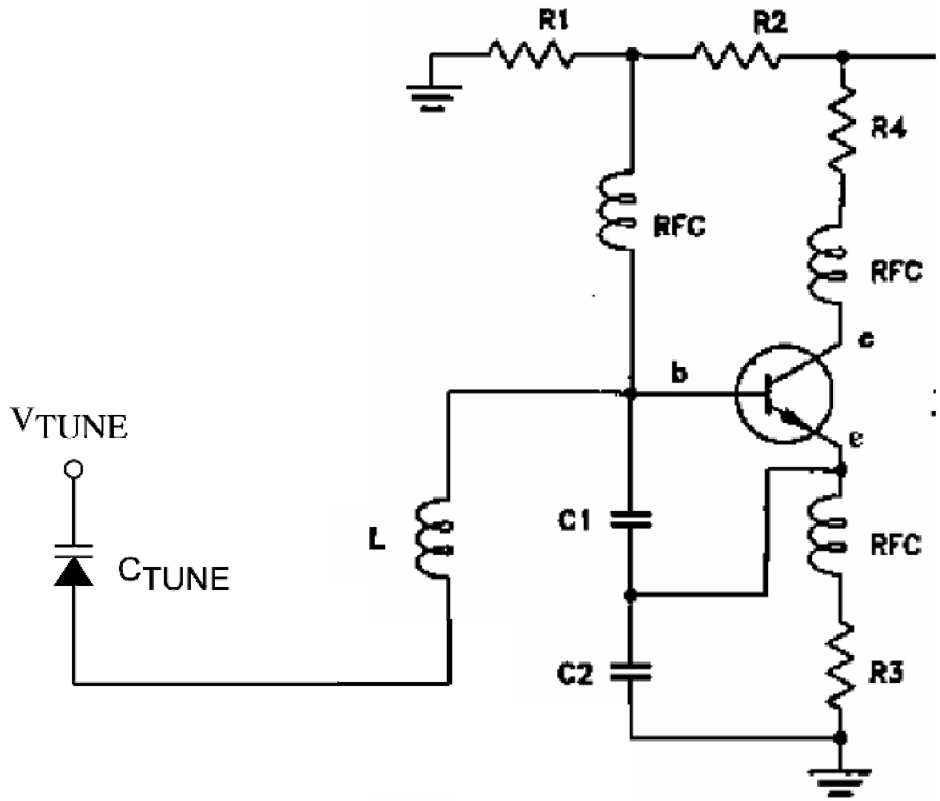
- **Ideally tuning voltage is the only way to change output frequency**
  - **In reality other factors involved**
  - **Mechanism depends on specifics of circuit**
- **Power supply dependence: Supply Pushing**
- **Impedance mismatch at output: Load Pulling**

Supply Pushing



- Change in f_{OSC} due to change in supply voltage
- Clapp oscillator: supply affects transistor bias condition, internal signal amplitudes

Load Pulling



- Change in f_{OSC} due to impedance mismatch at output
- Clapp oscillator; reflection couples through transistor parasitic to LC resonator

Overview

- Functional Block Concept
- Oscillator Review
- Basic Performance Metrics
- Methods of Tuning
- Advanced Performance Metrics
- **Conclusion**

Summary: VCO Fundamentals

- **First order behavior**
  - Tuning voltage V_{TUNE} controls output frequency
  - Specify by min/max range of f_{OSC}, V_{TUNE}
- **Performance limitations**
  - Linearity of tuning characteristic
  - Spectral purity: phase noise, harmonics
  - Supply, load dependence
- **Different VCO architectures trade frequency range, tuning linearity, phase noise performance**

Questions?

Thank you to our presenter John McNeill and our sponsor Mini-Circuits