SpectreRF Periodic Analysis

Switched capacitor Circuit Simulation

Agenda

- Sampled data systems
- Brief explanation and usage of PAC/PXF analyses in SpectreRF
- PNOISE Analysis
- Simulation Examples
  - Simple S/H
  - Switch capacitor buffer
  - T/R

SpectreRF Analyses

- PSS – Periodic Steady State Analysis
- PAC – Periodic AC Analysis
- PSTB – Periodic Stability Analysis
- PXF – Periodic Transfer Function
- PNoise – Periodic Noise Analysis
- PDist – Periodic Harmonic Distortion Analysis
- QPSS?

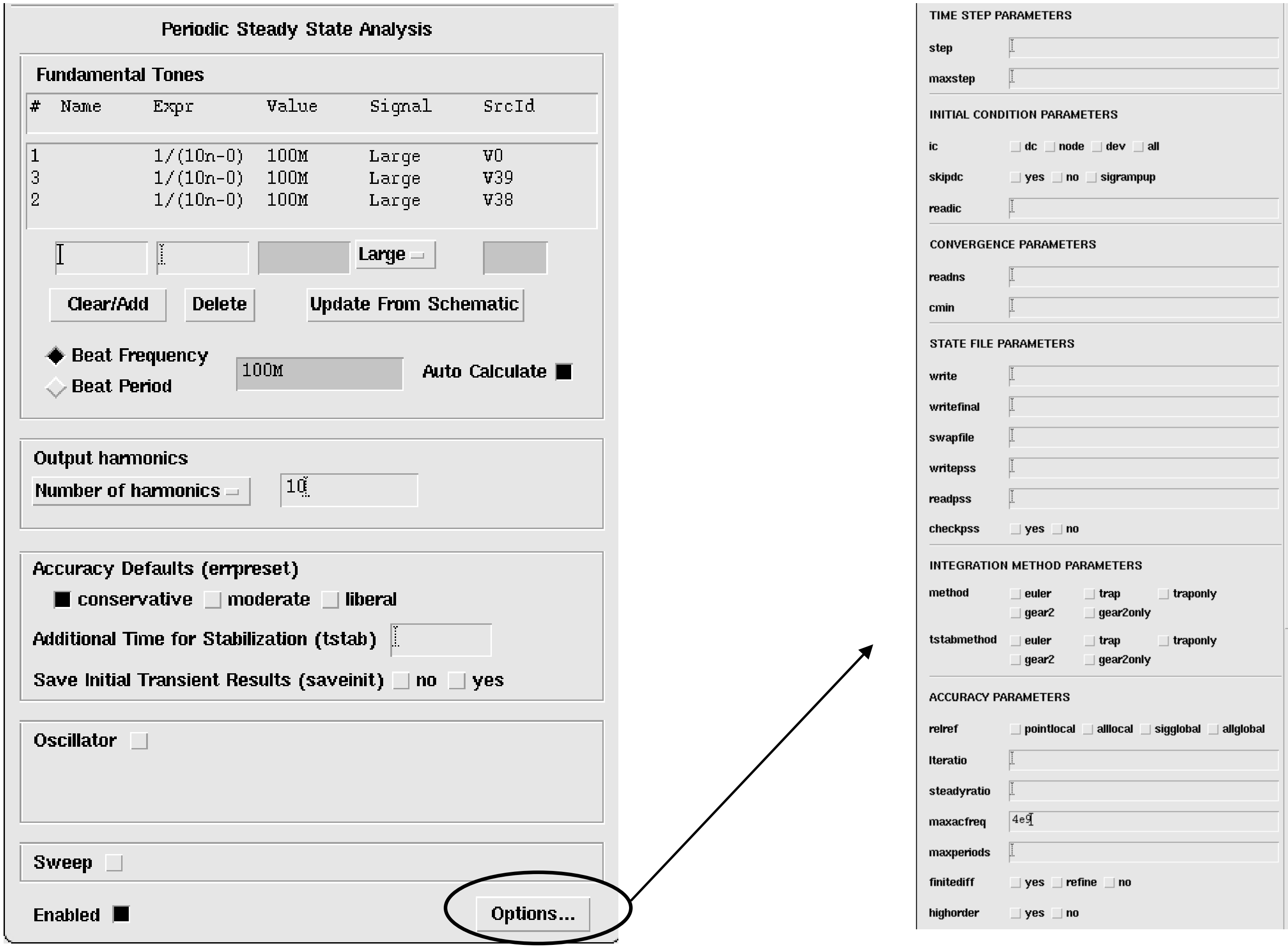
PSS Analysis

- Periodic Steady-State Analysis

- PSS calculates the period operating point
  - Required for other small-signal analyses (PAC, PXF, PNoise)
  - Only clock is applied, transient input disabled

- PSS Cadence parameters
  - *harmonics* specifies requested output harmonics to be viewed
  - *maxacfreq* is an accuracy parameter that specifies the maximum frequency that will be used in any subsequent small-signal analyses (4x*harmonics* by default)
  - Recommended formula:

  - *f*stop is maximum frequency of PAC/PXF/etc. sweep range
  - *maxsideband* specified in PAC/PXF/etc.
  - *f*s is clock frequency


Periodic Steady State Analysis
Fundamental Tones
Name Expr Value Signal SrcId
1 1/(10n-0) 100M Large V0
3 1/(10n-0) 100M Large V39
2 1/(10n-0) 100M Large V38
Large
Clear/Add
Delete
Update From Schematic
Beat Frequency
Beat Period
100M
Auto Calculate
Output harmonics
Number of harmonics
10
Accuracy Defaults (errpreset)
conservative
moderate
liberal
Additional Time for Stabilization (tstab)
Save Initial Transient Results (saveinit)
no
yes
Oscillator
Sweep
Enabled
Options...
TIME STEP PARAMETERS
step
maxstep
INITIAL CONDITION PARAMETERS
ic
dc
node
dev
all
skipdc
yes
no
sigrampup
readic
CONVERGENCE PARAMETERS
readns
cmin
STATE FILE PARAMETERS
write
writefinal
swapfile
writepss
readpss
checkpss
yes
no
INTEGRATION METHOD PARAMETERS
method
euler
trap
traponly
gear2
gear2only
tstabmethod
euler
trap
traponly
gear2
gear2only
ACCURACY PARAMETERS
relref
pointlocal
alllocal
sigglobal
allglobal
lteratio
steadyratio
maxacfreq
4e9
maxperiods
finitediff
yes
refine
no
highorder
yes
no

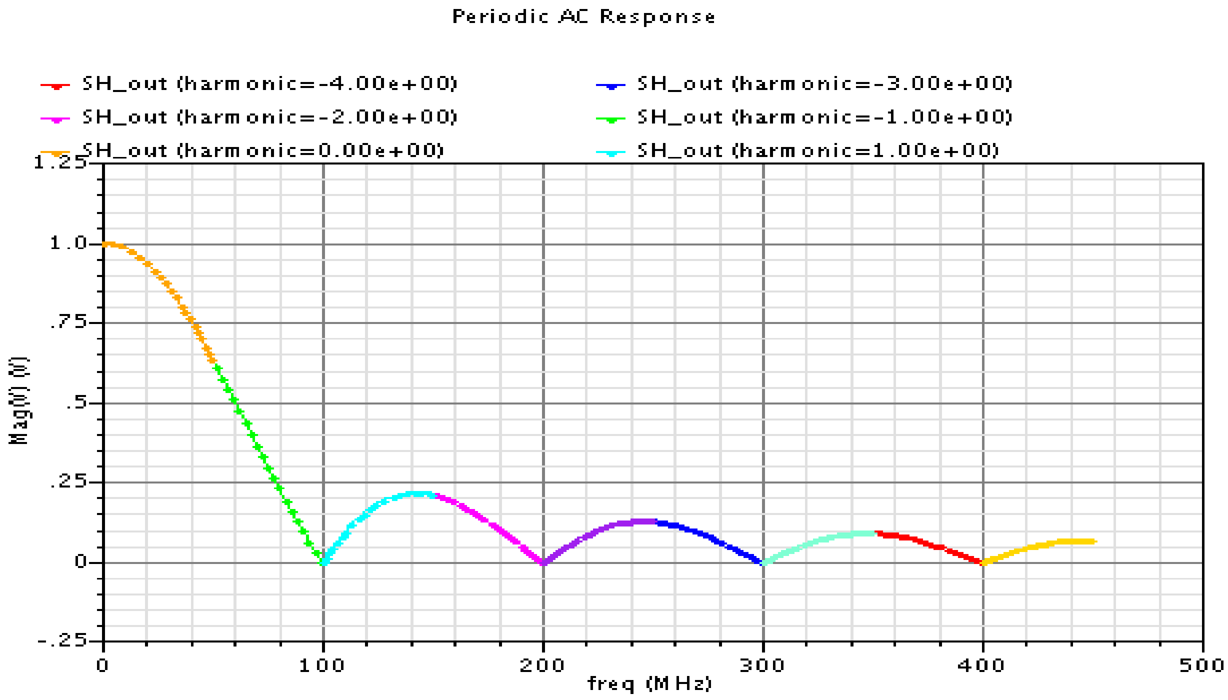
PAC Analysis

- Periodic AC Analysis

- PAC "computes the output signal at every node and every sideband given a single input"1
  - Creates a mapping between an input freq range and each resulting output freq range due to modulation
  - Use PAC to find how an interesting input frequency is modulated and attenuated to resulting frequencies at the output

- PAC Cadence parameters
  - Specified sweep frequency is the INPUT frequency range
  - *maxsideband* determines the number of output frequency bands calculated by Cadence to which the input range is modulated
  - Set *pacmagnitude* in source to 1V
  - Can choose any circuit node as PAC output

PAC Analysis

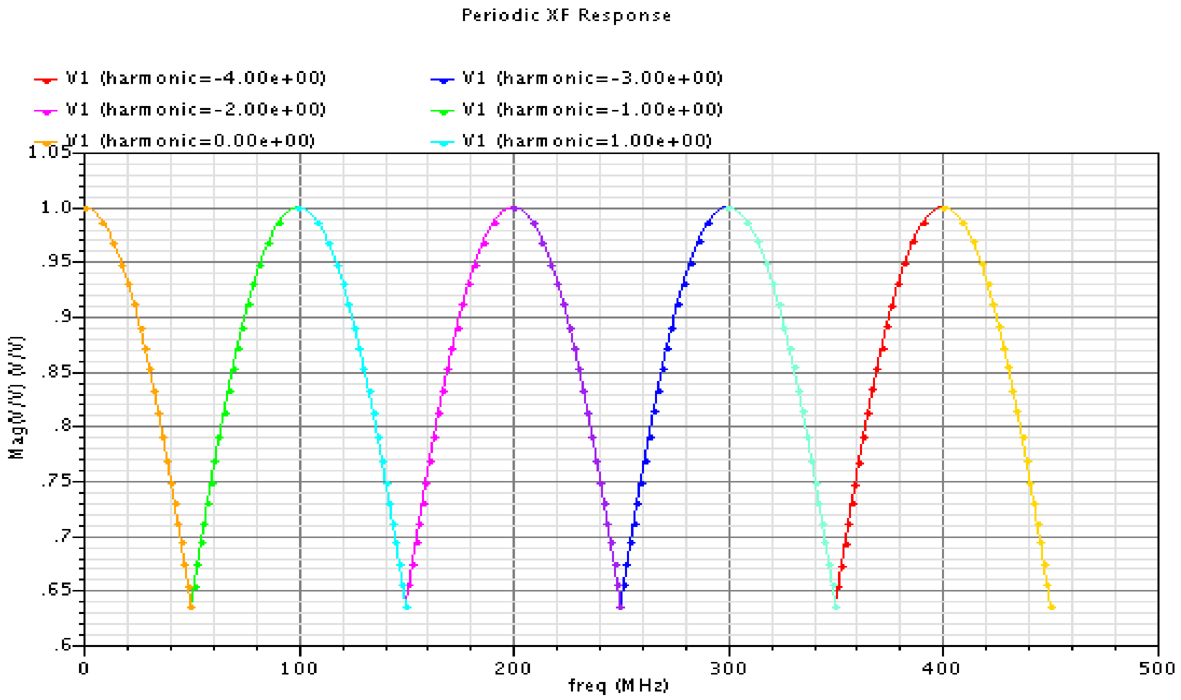


- Sweeping PAC input frequency from 0 → fs/2 shows the modulation of the input signal baseband into all of the specified output bands …perfect for nyquist band limited input signals
- Sweeping past fs/2 shows the modulation of higher input signal bands into all of the specified output bands

PXF Analysis

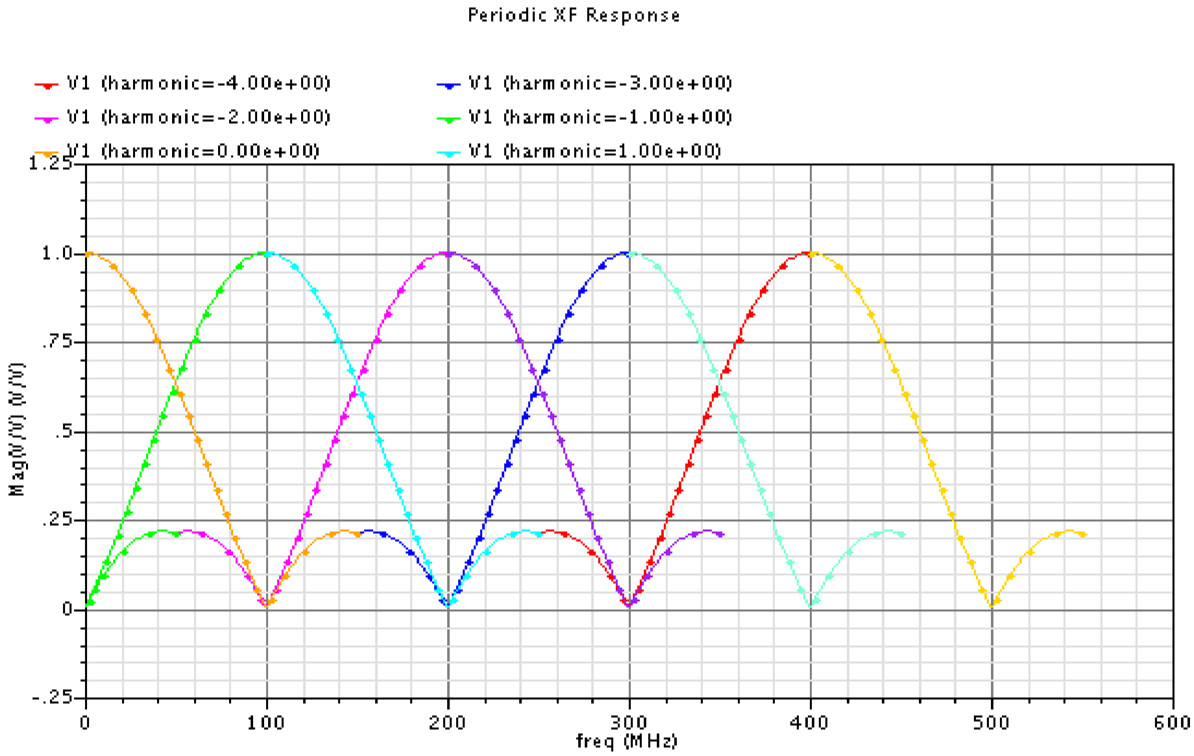
- Periodic Transfer Function Analysis
- PXF "computes the transfer function from every input source at every sideband to a single output"1
  - Creates mapping between a particular output frequency and the combination of modulated input frequencies that compose it
  - Use PXF to find the input frequency composition of an interesting output frequency
- PXF Cadence parameters
  - Specified sweep frequency is the OUTPUT frequency range
  - *maxsideband* specifies the number of input frequency bands calculated by Cadence that are modulated into the output frequency range
  - Set specific output node in analysis form
  - Can choose any source in the circuit to view XF to the output

PXF Analysis



- Sweeping PXF from 0 → fs/2 shows how all of the chosen input frequency bands modulate into the output baseband
- Each color curve segment represents the output baseband where the starting harmonic is DC

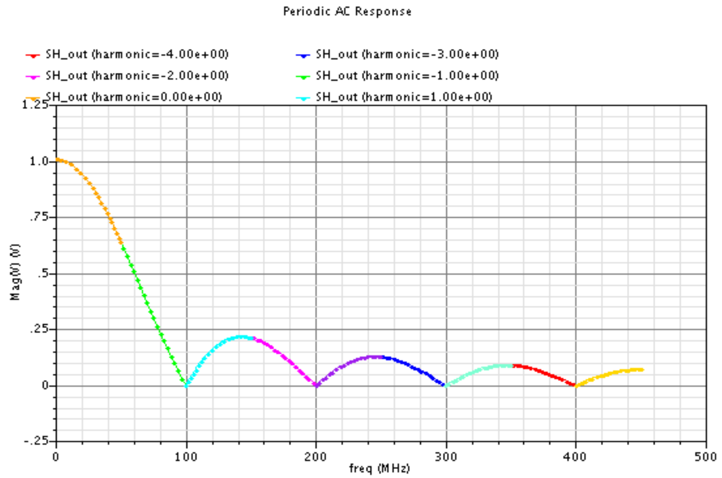
PXF Analysis

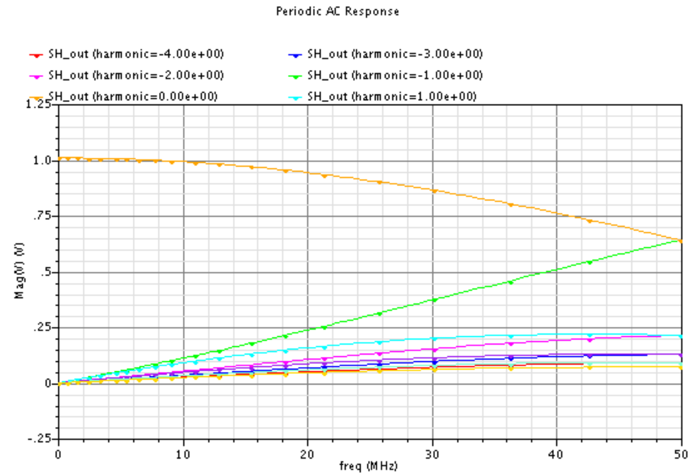


- Sweeping PXF past fs/2 shows how the specified input frequency bands modulate into higher output bands

Comment About PAC/PXF Sweep Type

- Previous results have been plotted for linear sweeps
- Logarithmic sweeps refer all waveforms into frequency sweep range:
  - PAC – all output sidebands are shown as folded into the input frequency sweep range. Output signal frequency information not shown.
  - PXF – input sideband contributions are folded into output frequency sweep range. Information relating contributions to input frequencies not shown.
- Example: PAC linear sweep (left), log sweep (right, changed to lin axis)





PXF vs PAC

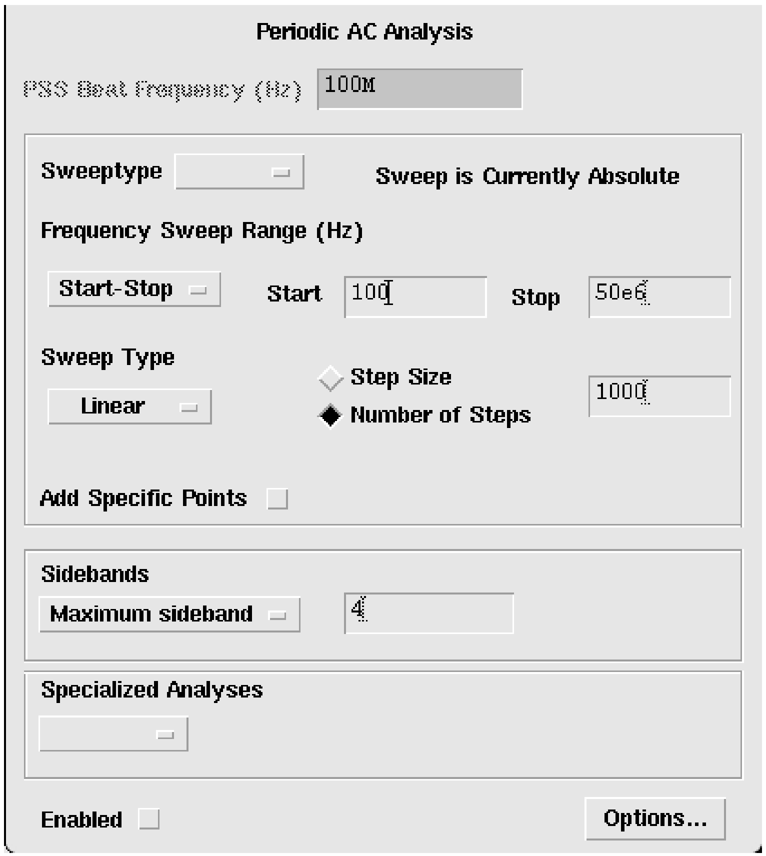
PAC

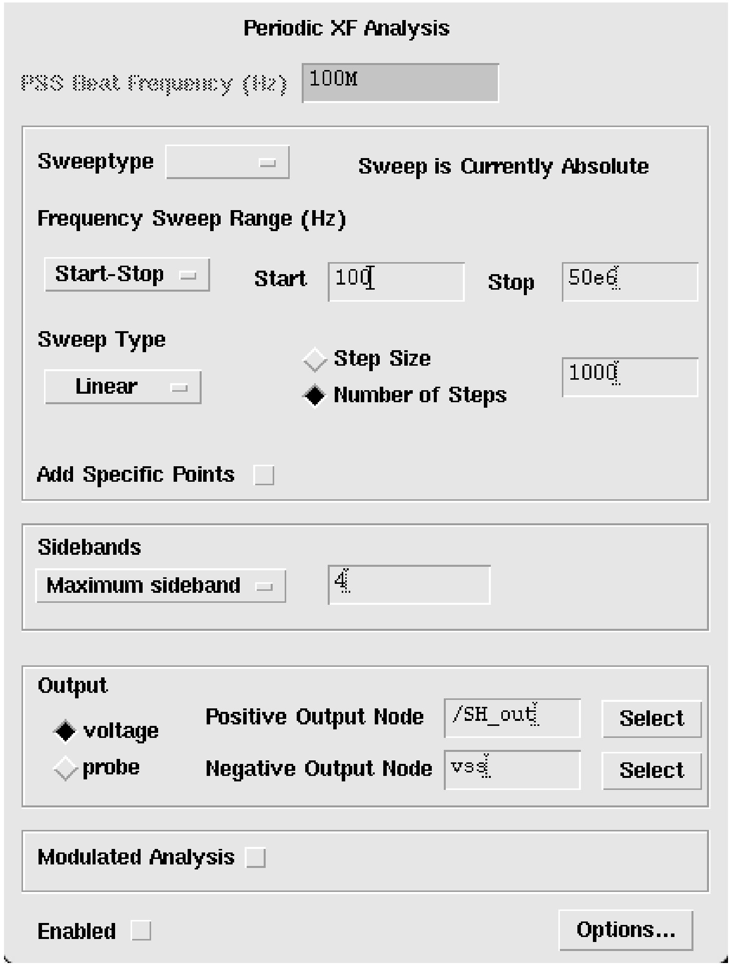
I know my input signal, how does this become my output signal?

PXF

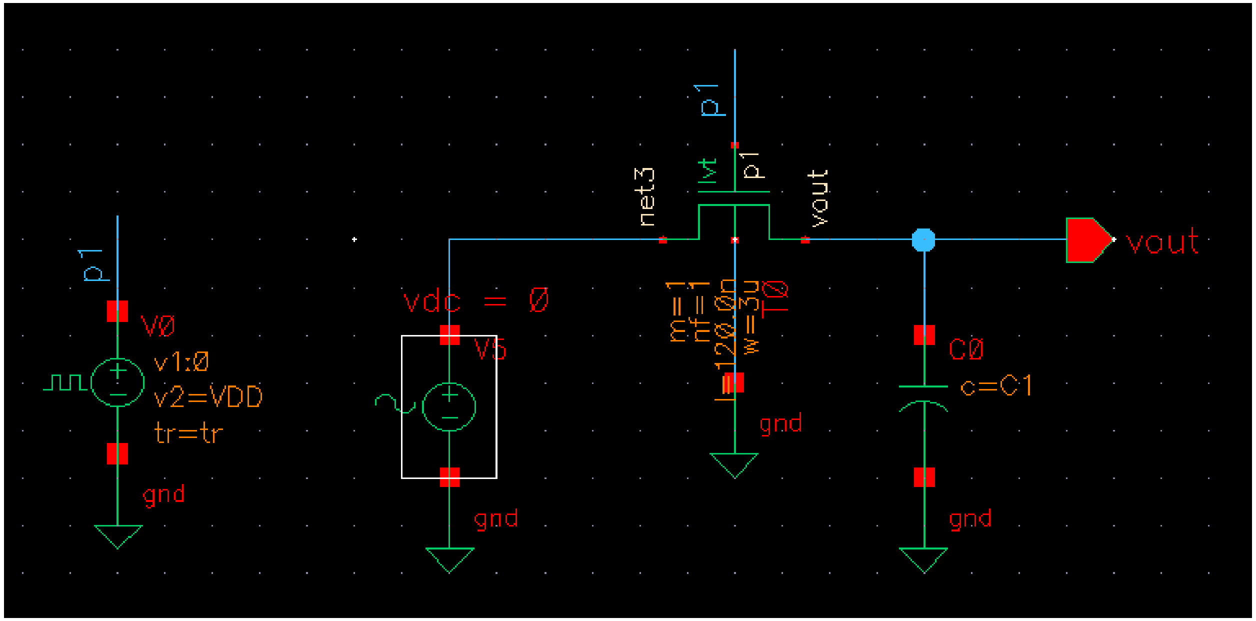
I know my output signal, how does this come from my input signal?

SpectreRF PAC/PXF Analysis Forms



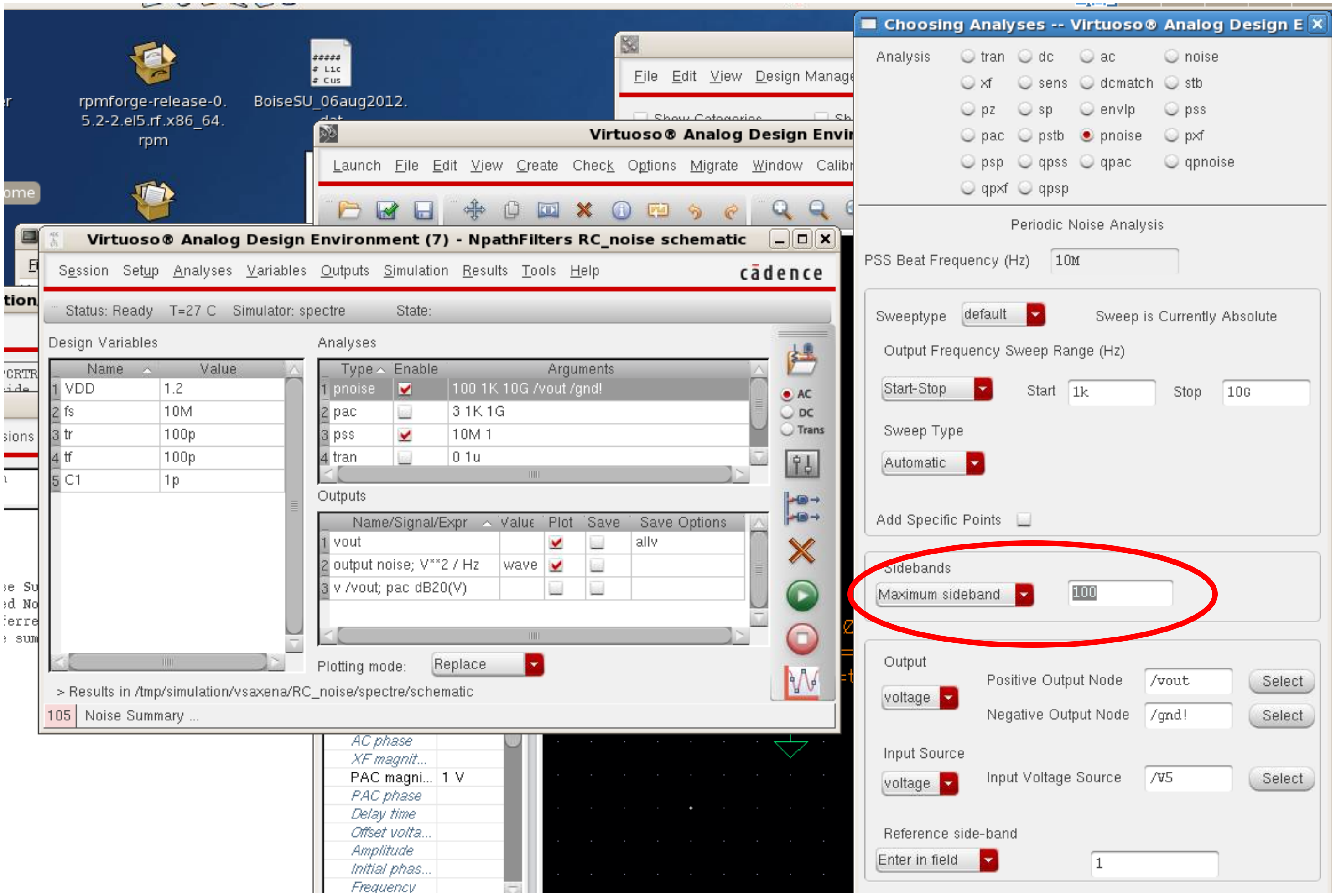


PNOISE Analysis



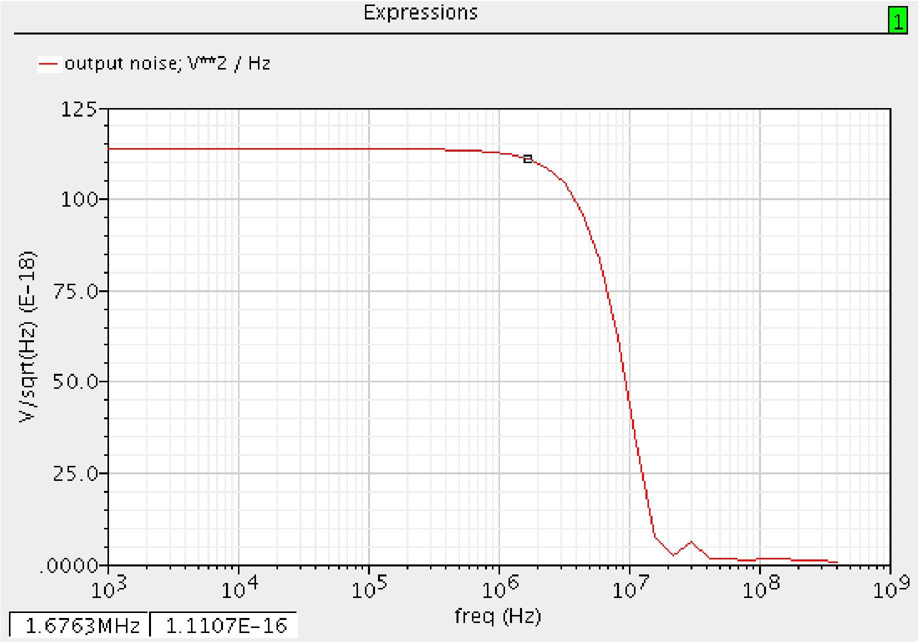
- ❑ Simulation of noise in sampled circuits
- ❑ Example: Switch-C circuit
  - ▪ Here an NMOS switch with C=1pF, f_{clk}=10MHz
- ❑ Set up PSS analysis for the f_{clk}=10MHz clock

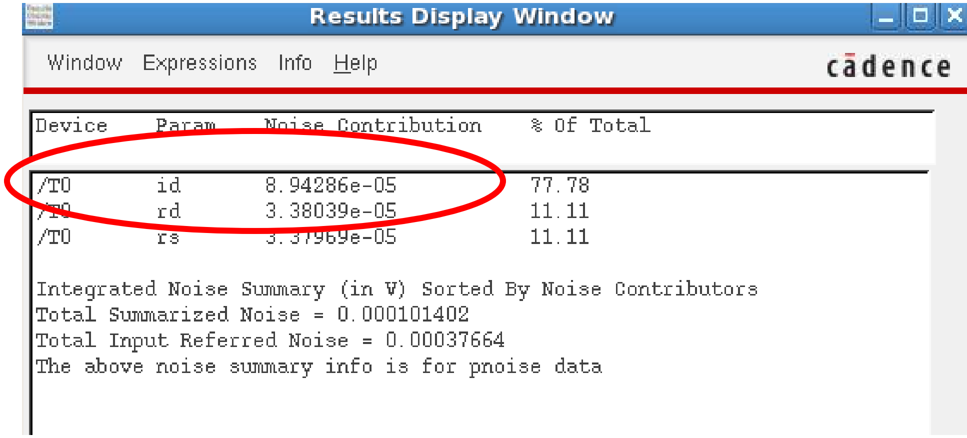
PNOISE Analysis



- Include sufficient number of *maxsideband* for accuracy

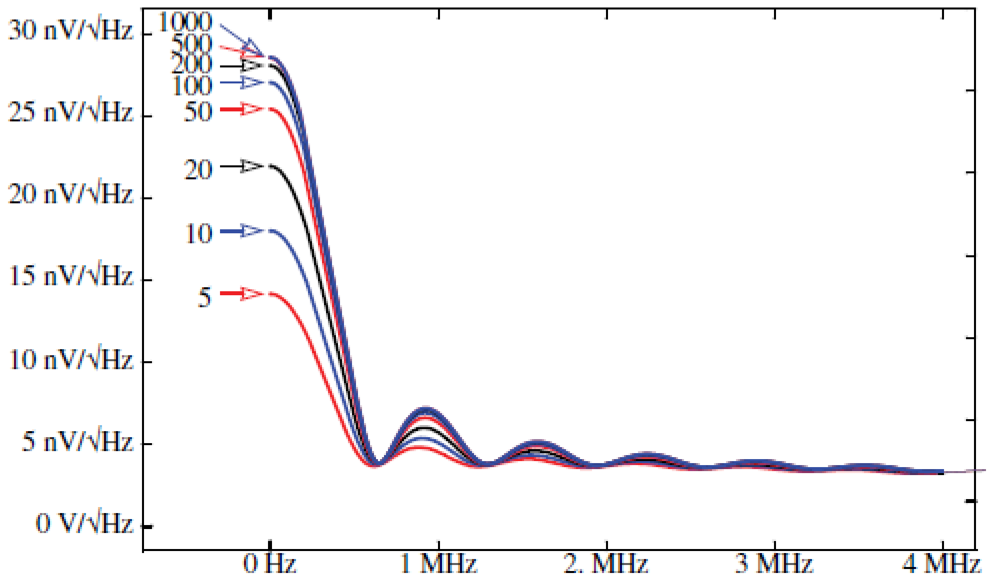
PNOISE Analysis





- Simulation shows 89µV of output RMS noise
  - Ideal √(kT/C) value =64µV,
  - Simulation results close to the approximation of √(kT/C)

PNOISE Analysis

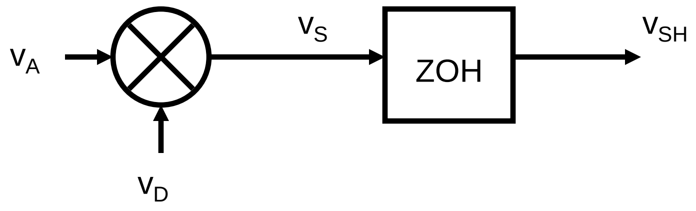


- Accuracy is tightened by using large number of *maxsideband* parameter
  - Determines how many sideband alias into the given band
  - Trades-off simulation time with accuracy
- For analytical details, refer to:

http://www.designers-guide.org/analysis/sc-filters.pdf

Sampled Signal Analysis

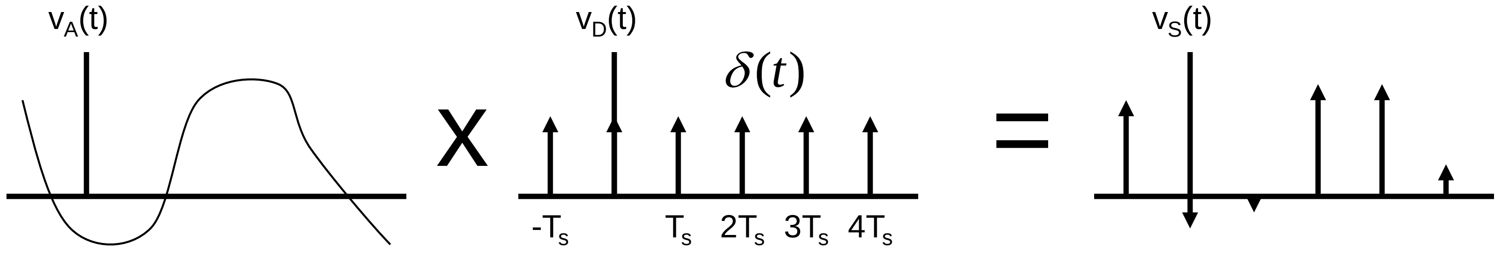
• A Sample and hold (S/H) is analyzed in the time domain as an ideal sampler in cascade with a zero-order hold (ZOH)



$$v_{SH} = v_S * ZOH = (v_A \cdot v_D) * ZOH$$

$$v_D(t) = \sum_{k=-\infty}^{\infty} \delta(t - kT_s)$$

• The ideally sampled signal $v_S(t)$ is obtained by multiplying input with periodic pulse train



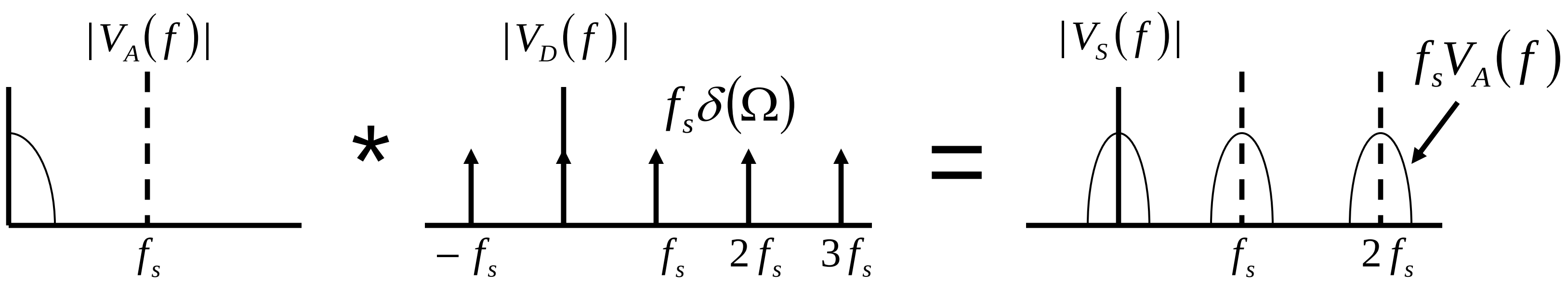
Sampled Signal Analysis

- The frequency spectrum of the impulse train is found from the fourier transform of the fourier series representation

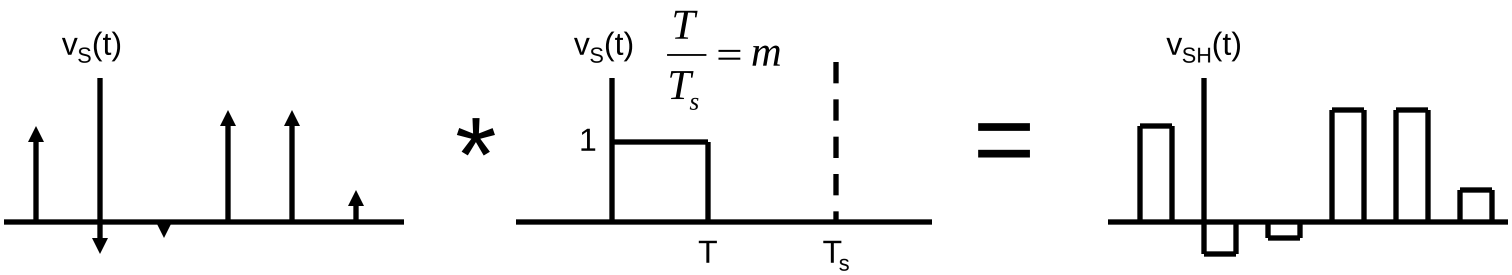
$$v_D(t) = \sum_{k=-\infty}^{\infty} \delta(t - kT_s) = \sum_{n=-\infty}^{\infty} \frac{1}{T_s} e^{jn \cdot 2\pi f_s t} \Leftrightarrow V_D(f) = \sum_{n=-\infty}^{\infty} f_s \cdot \delta(f - nf_s)$$

- Multiplying with pulse train in time domain → convolving with pulse train in frequency domain

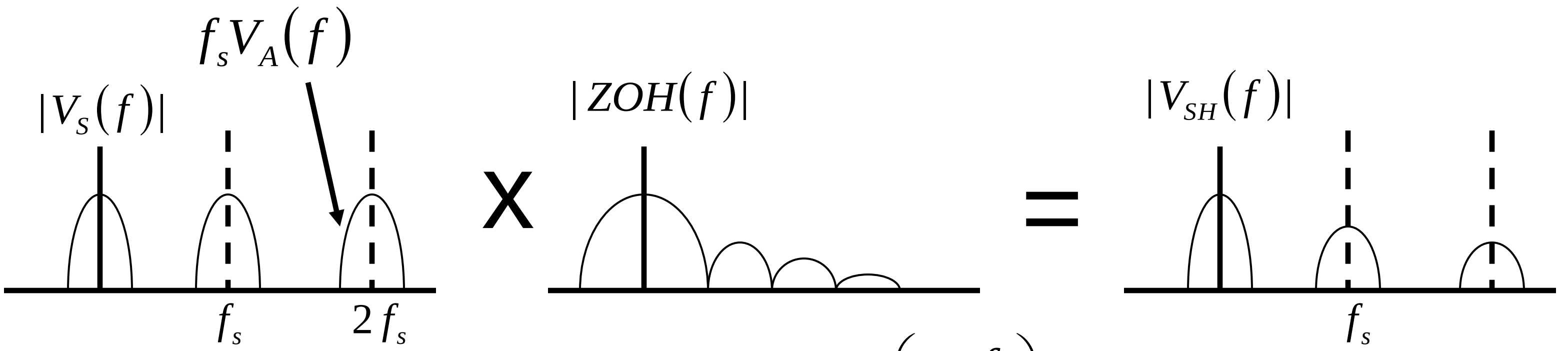
$$f_s = \frac{1}{T_s}$$



- The S/H output is found by convolving $v_S(t)$ with the cascaded ZOH impulse response (a unit pulse, a fraction of the sampling period)



- Convolving with ZOH in time domain → multiplying with sinc in frequency domain



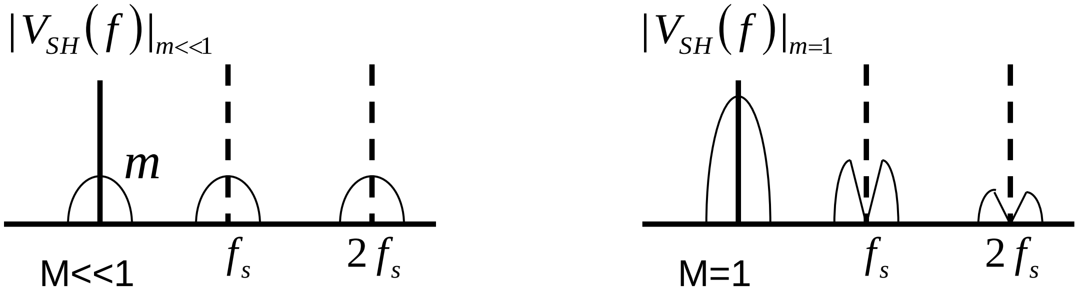
$$ZOH(f) = mT_s \cdot \text{sinc}\left(m\frac{f}{f_s}\right)$$

Sampled Signal Analysis

- Result is the baseband filtered by the sinc main lobe, plus frequency periodic baseband replicas filtered by the sinc side lobes

$$V_{SH}(f) = mT_s \cdot \mathrm{sinc}_\pi\left(m\frac{f}{f_s}\right) \cdot \sum_{n=-\infty}^{\infty} f_s \cdot V_s(f - nf_s) = m\,\mathrm{sinc}_\pi\left(m\frac{f}{f_s}\right)\sum_{n=-\infty}^{\infty} V_s(f - nf_s)$$

- Shape of sinc function (and filtering of spectrum) depends on S/H duty cycle (m)
  - m<<1: sinc is wide but short, attenuation but little shaping of baseband or near images
  - m=1: sinc thin and tall, significant shaping of baseband and images, zeros at $f = nf_s$



Sampled Signal Analysis

- Sampling into the digital domain (A/D converter) acts as an ideally sampled system and replicates the spectrum at all clock harmonics

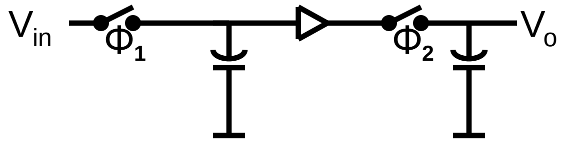
- Any spectrum energy outside of the Nyquist range gets folded/aliased into baseband

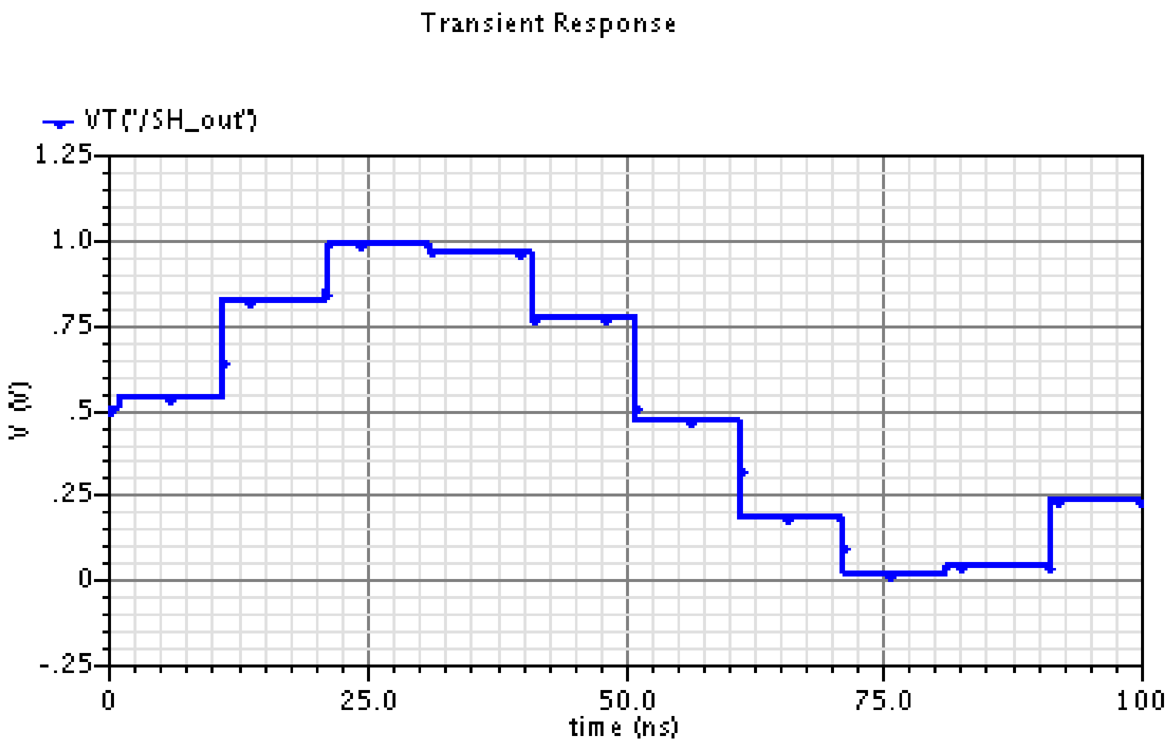
- SNR need be considered only within f=0→fs/2 because spectrum is symmetric about DC and repeats every fs (DTFT)

PXF/PAC Analyses for Basic Applications

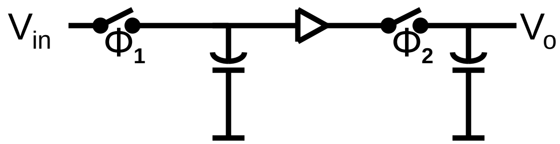
- Ideal Sample and Hold (S/H)
- RC Band-limited S/H
- Switch Capacitor (SC) Buffer

Ideal Sample and Hold (S/H)

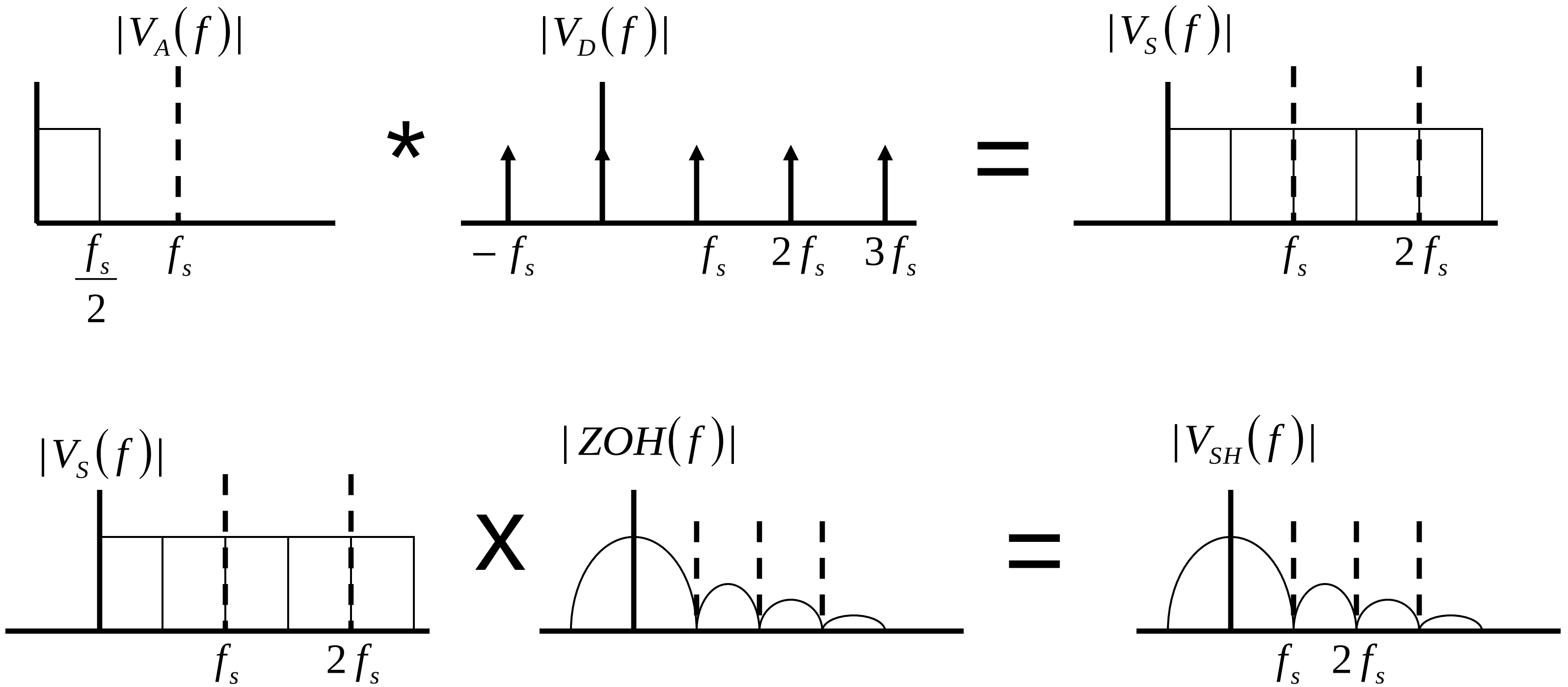




Expectation: Ideal S/H

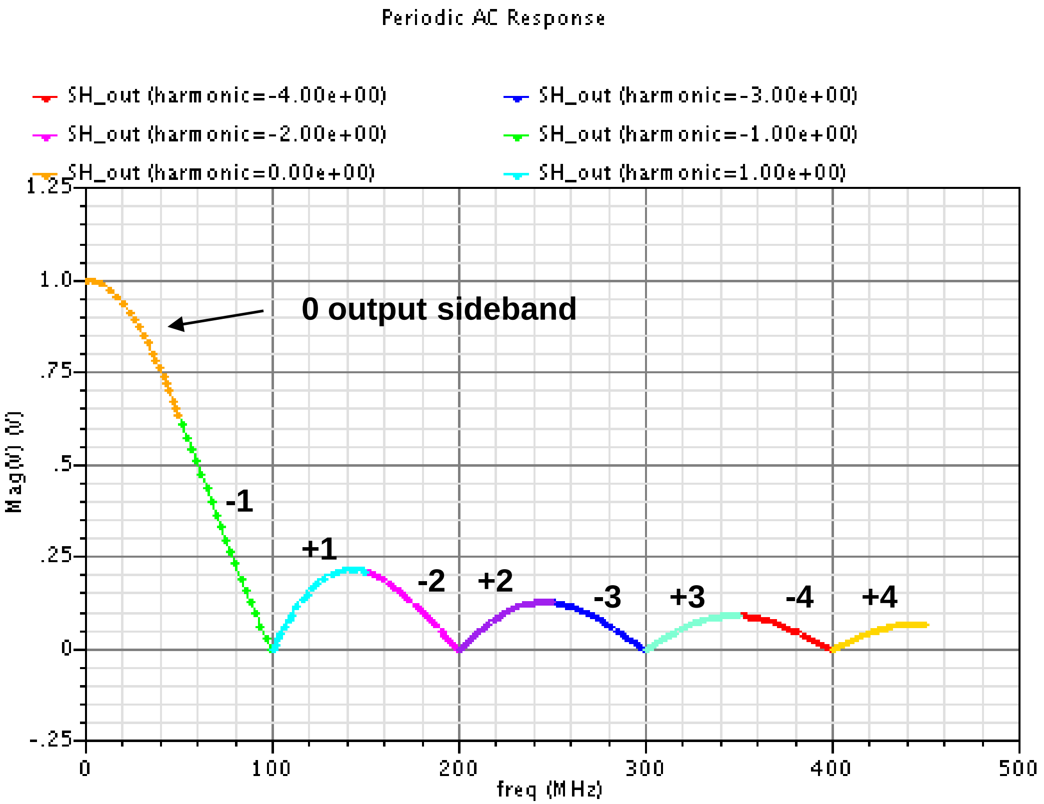


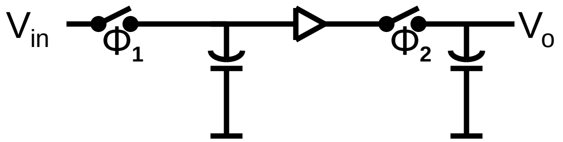
- Assume a unity, nyquist band-limited input
- Like a input band limited AC analysis (like a PAC)



PAC: Ideal S/H

- Sweep from 0→$f_s/2$: only looking at how input baseband modulates into other bands
- AC input is unity over all frequencies, therefore output is the sinc shaping of the modulated input baseband





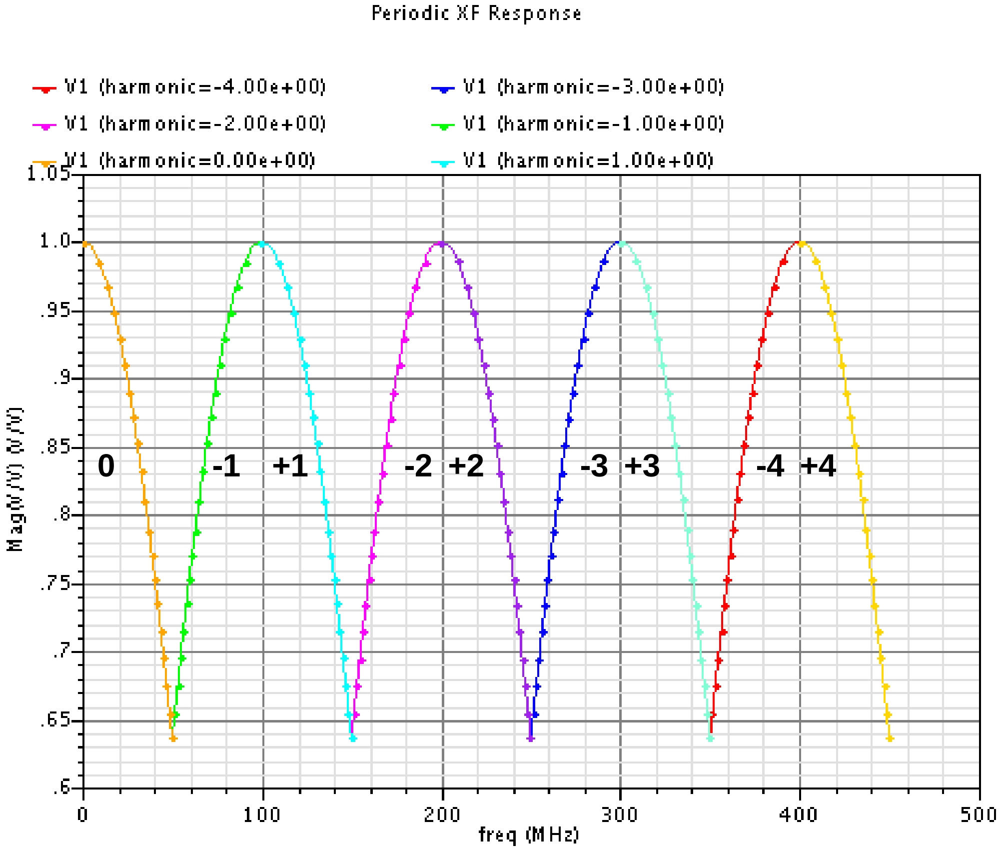
F_{clk}=100 MHz

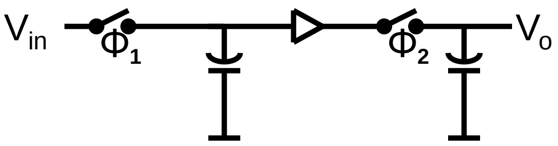
PSS beat freq=100M autocalculated
maxacfreq=default

PAC input frequency range
(100Hz , $f_s/2$=50MHz),
linear sweep, 1000 steps
maxsideband=4

PXF: Ideal S/H

- Sweep from 0→$f_s/2$: only looking at how input frequencies modulate into the output baseband
- Resulting curves only show output baseband shaping (main lobe of sinc)



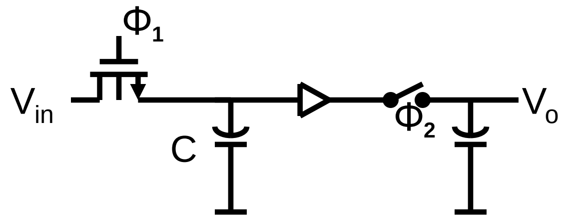


F_{clk}=100 MHz

PSS beat freq=100M autocalculated
maxacfreq=default

PXF output frequency range (100,50M)
linear sweep, 1000 steps
maxsideband=4

PAC: RC limited S/H

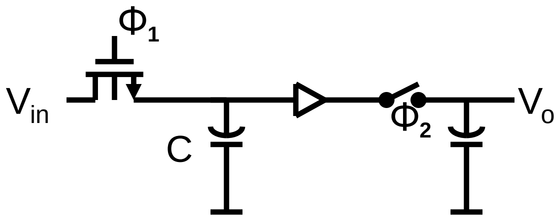


• Baseband input should modulate to output bands similarly to ideal case if RC constant designed correctly (PAC)

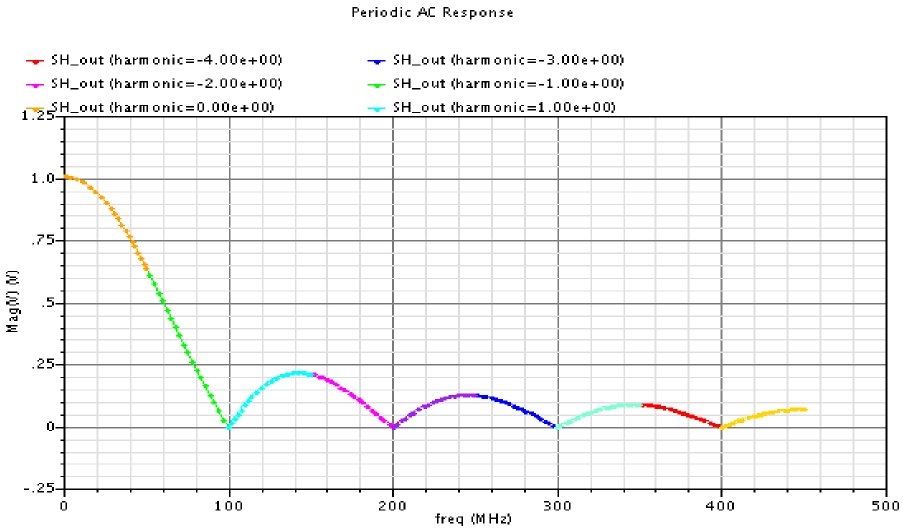
• S/H now has limiting bandwidth, so higher input frequencies will attenuate when modulating into output baseband (PXF)

• Set 1/RC = 2*pi*f_{clk}*7 => 700 MHz: C=1pF, R~230 ohms, W/L=9u/.18u

PXF: RC limited S/H



- Baseband input should modulate to output bands similarly to ideal case if RC constant designed correctly (PAC)



F_{clk}=100 MHz

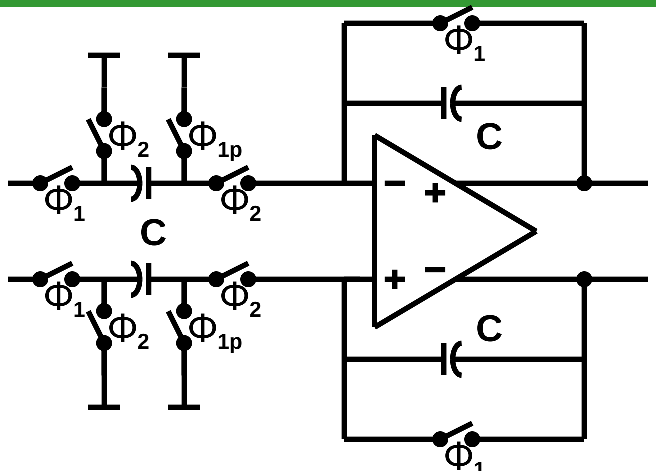
PSS beat freq=100M autocalculated
maxacfreq=default

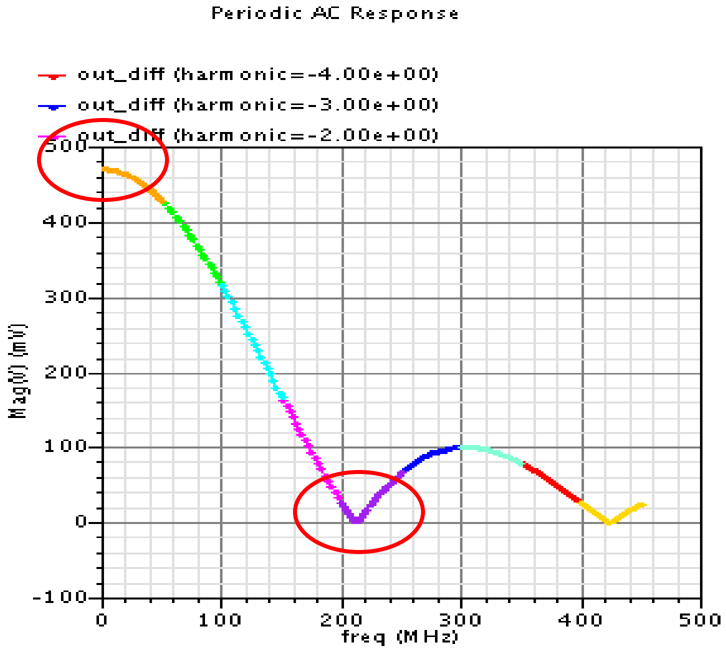
PAC input frequency range (100Hz ,50MHz), $f_s/2$
linear sweep, 1000 steps
maxsideband=4

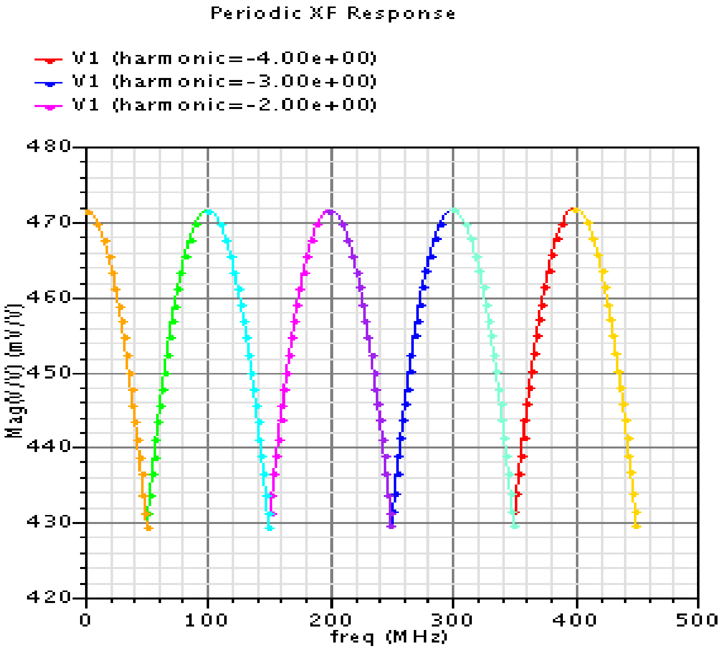
SC Buffer

- Ideal switches, no resistance
- Ideal OpAmp, no BW limit
- Sinc shaping slightly off due to reduction of duty cycle for non-overlapping phases

$$ZOH(f) = mT_s \cdot \mathrm{sinc}_\pi\left(m\frac{f}{f_s}\right)$$

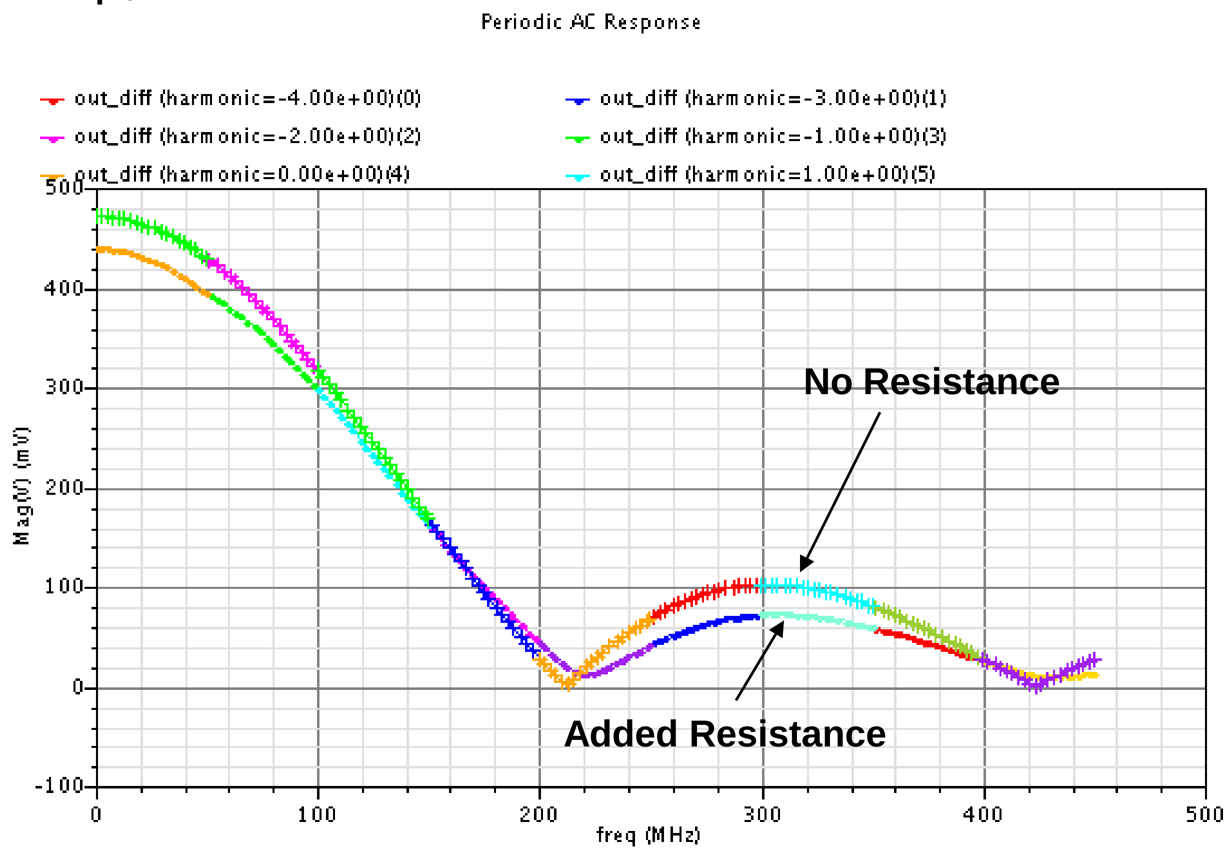






SC Buffer

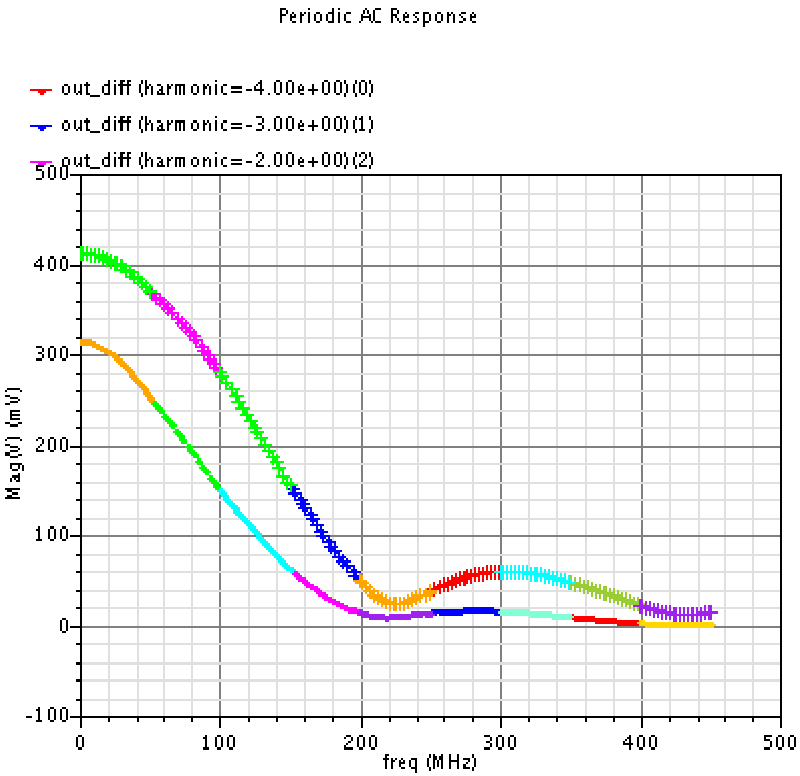
- Ideal switches with resistance
- Ideal OpAmp, no BW limit

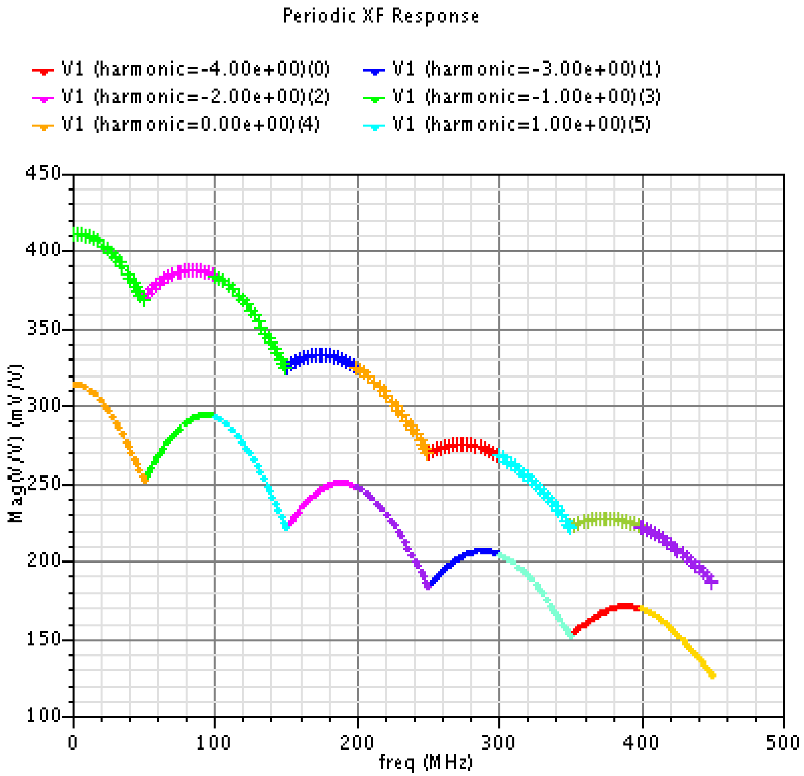


Adding the switch resistance of the SC Buffer: PAC

SC Buffer

- Ideal switches with resistance
- Ideal OpAmp with limited BW

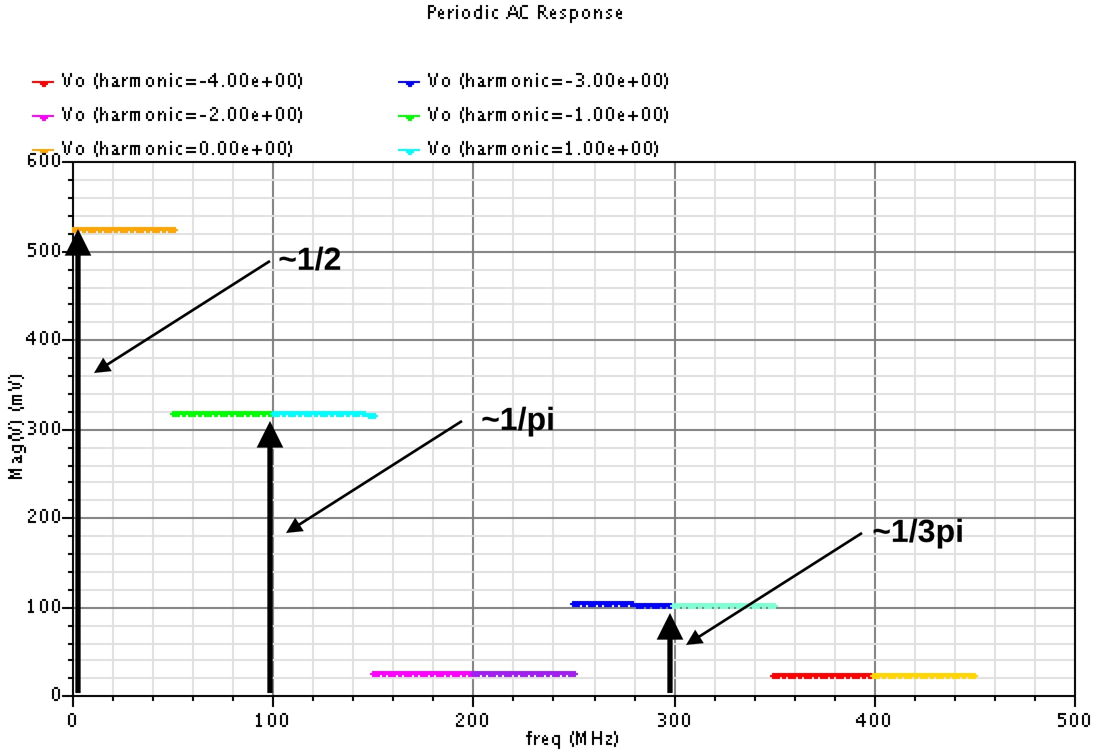




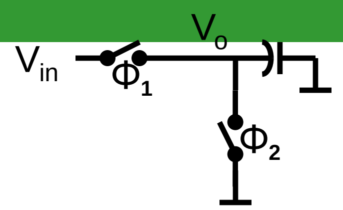
Reducing the BW of the SC Buffer OpAmp: PAC (left) PXF (right)

Track and Reset

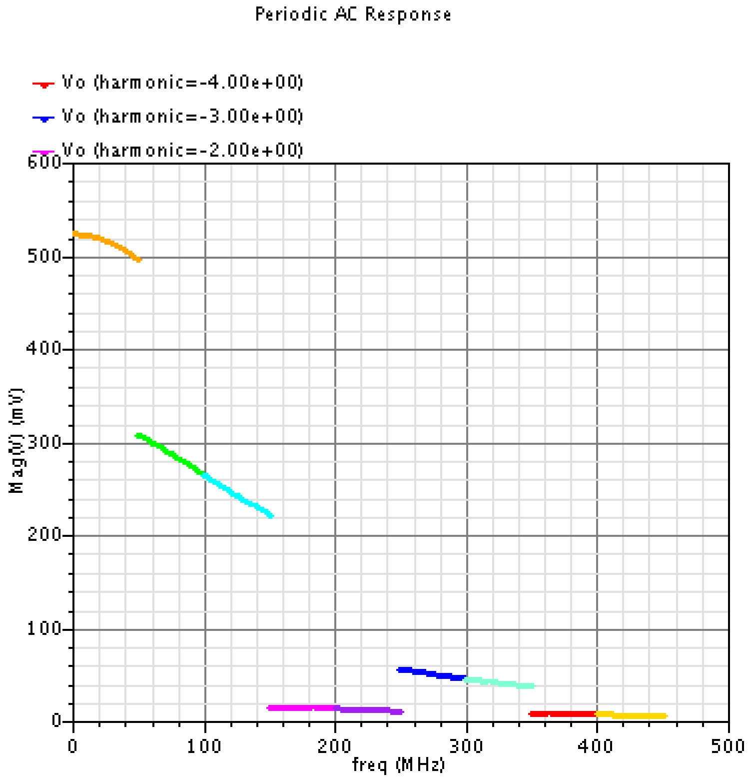
- Ideal track and reset:
  - Analyzed as input multiplied by pulse train
  - Result is passband modulated by pulse train tones
  - No resistance yields no shaping in bands
  - Pulse train tones off due to non-overlapping clocks
  - PAC and PXF look identical

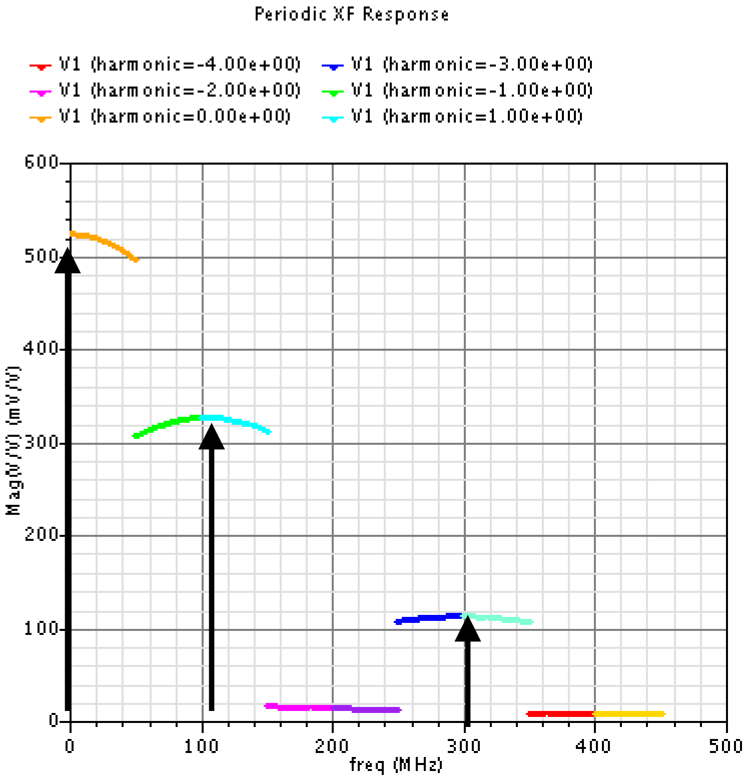


Track and Reset



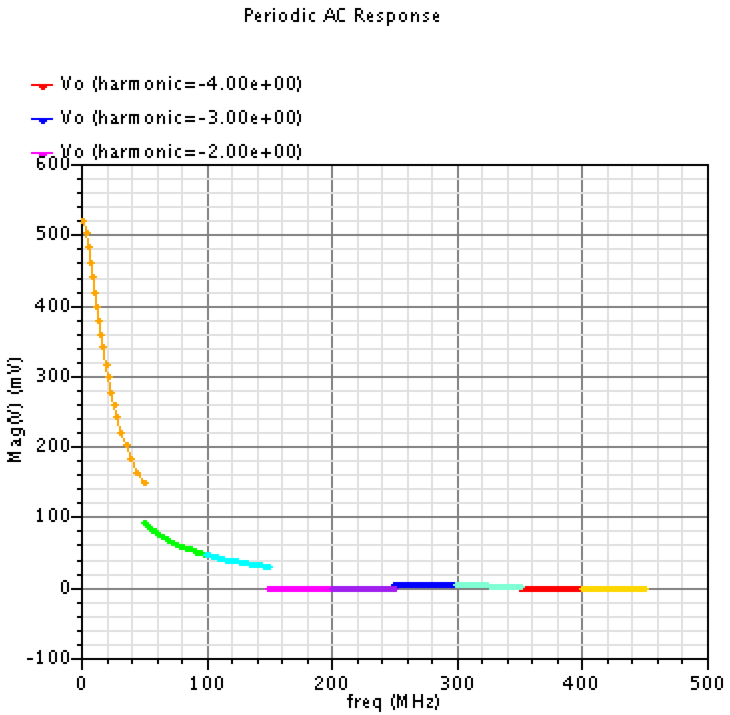
- Real track and reset:
  - Added switch resistances (R=1k, C=1p)
  - Results in shaped, modulated passbands
  - PAC: modulation from input passband into output sidebands
  - PXF: modulation from input sidebands into output passband

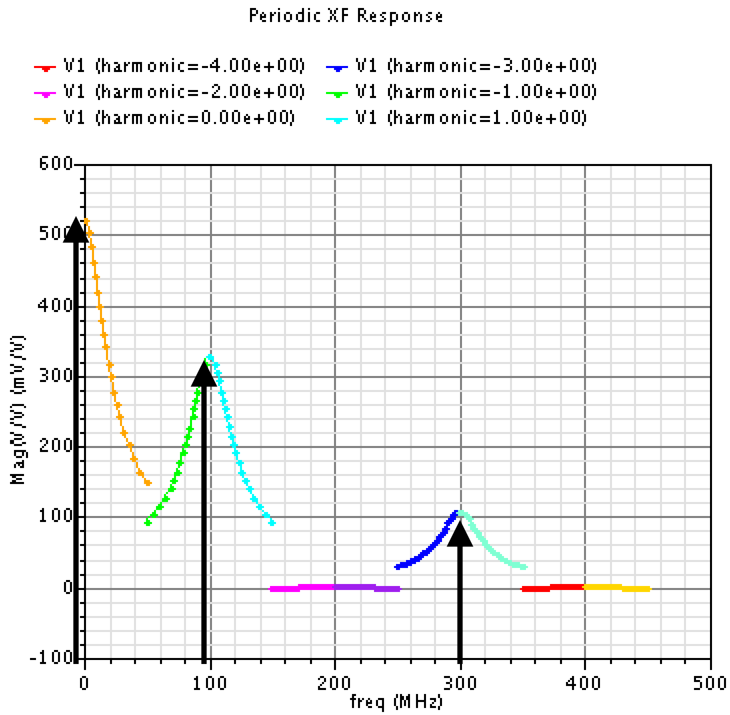




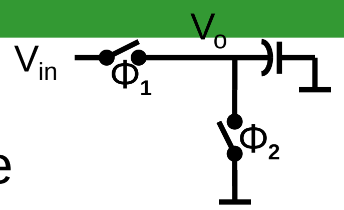
Track and Reset

- Real track and reset:
  - Excessive resistance (R=10k, C=1p)

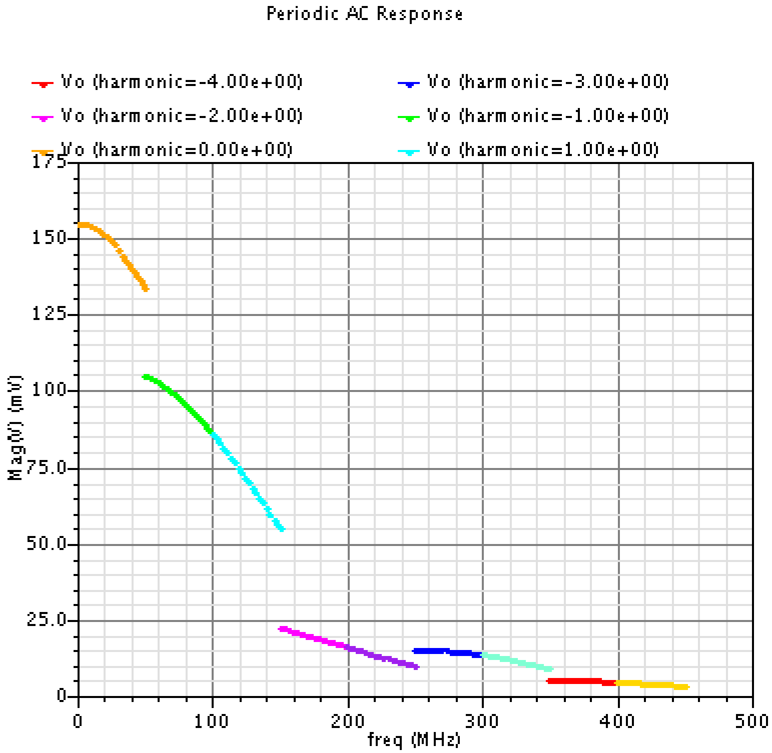


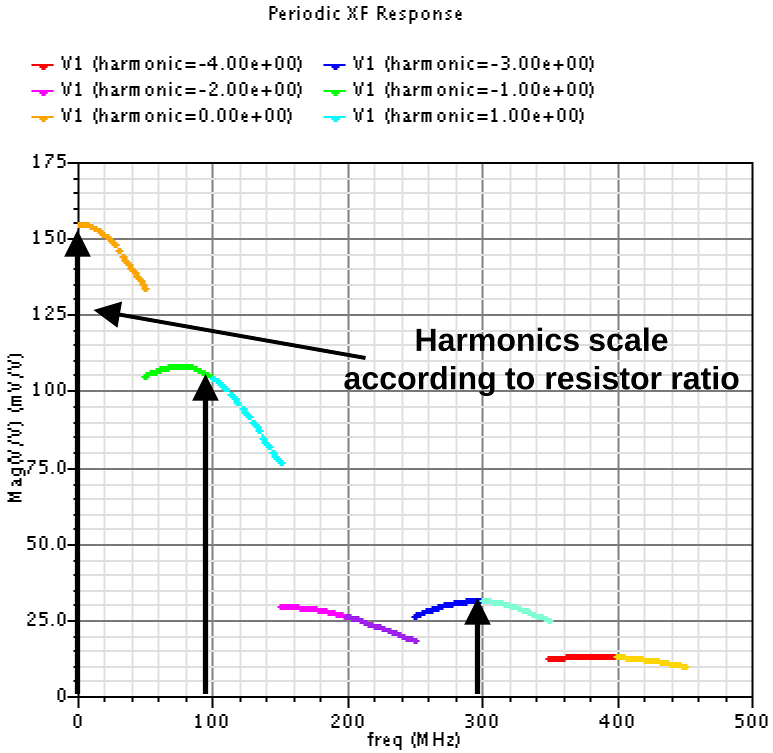


Track and Reset



- Real track and reset:
  - Changing the resistance ratio scales the response
  - DC and input clk harmonics modulating to output scaled by $2R_1R_2/(R_1+R_2)$ from ideal
  - R_1=10k, R_2=1k, C=1p





References

1. SpectreRF User Manual
2. Josh Carnes and Peter Kurahasi, “Periodic Analyses of Sampled Systems Using SpectreRF”
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