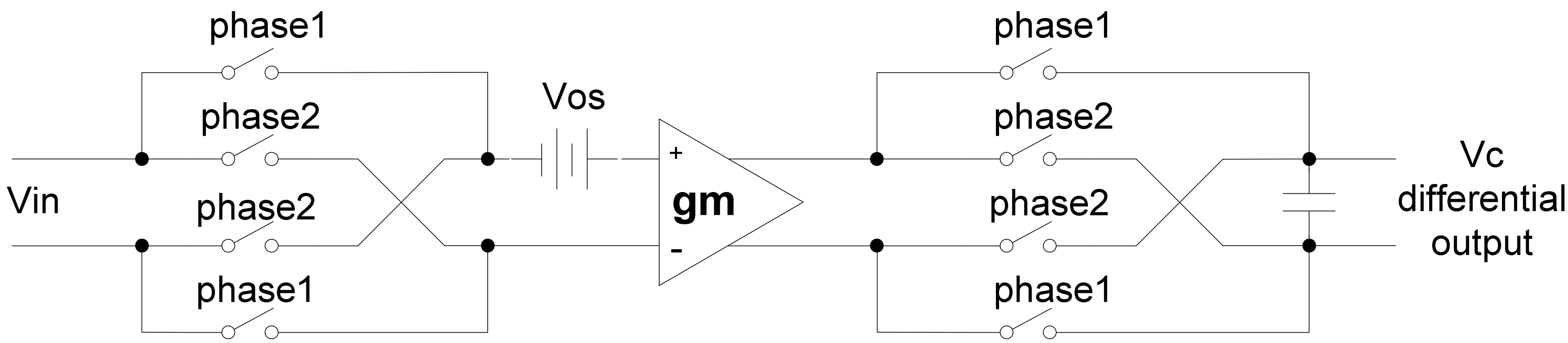
# Intrinsic Noise Sources in Chopper Amplifiers

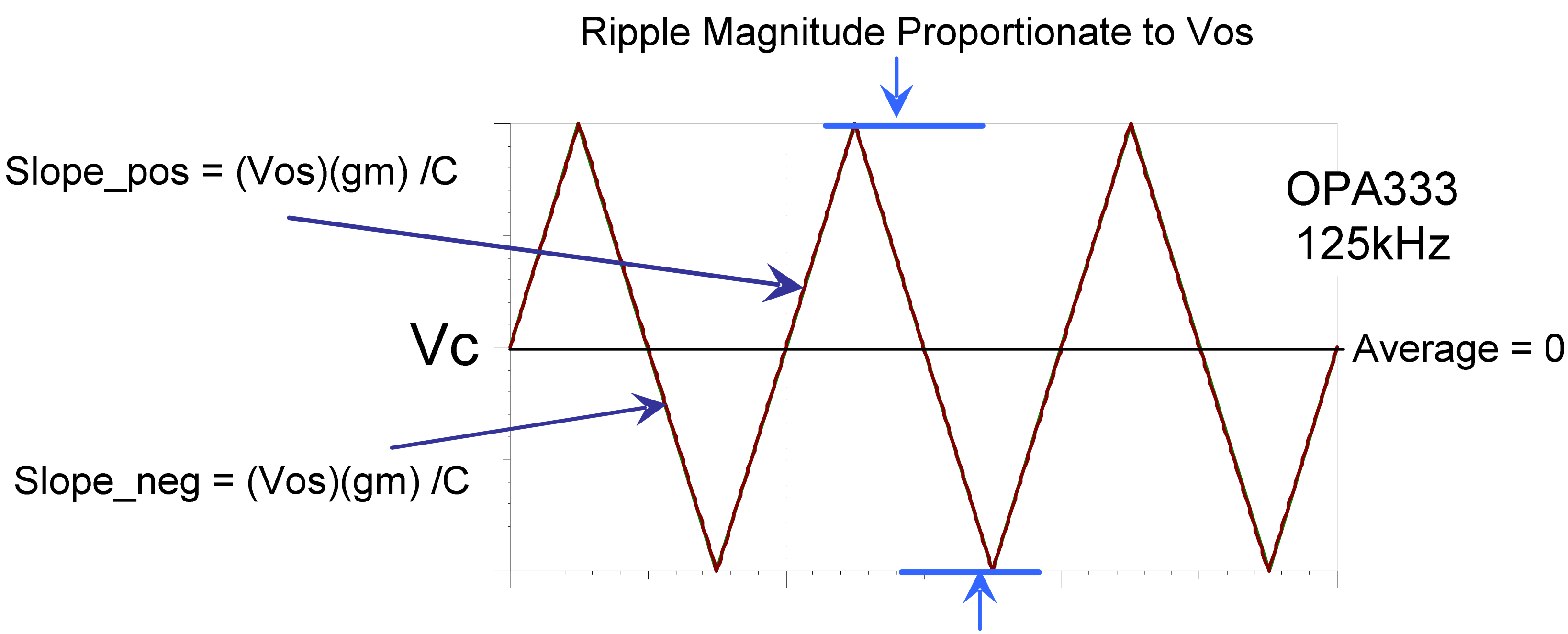
John Caldwell
Applications Engineer, Texas Instruments Precision Analog

# Agenda

- Chopper Amplifier Topology
  - Advantages over standard designs
- Chopper Intrinsic Noise Sources
  - Input Current Noise
    - Input Current Noise Calculation
    - Transient Noise
  - Input Voltage Noise
    - Effects of chopping on total integrated noise
    - Chopping in-band vs out-of-band
    - Gain effects
- Application Considerations

# Chopper Stabilized Topology



# Engineering Compromises

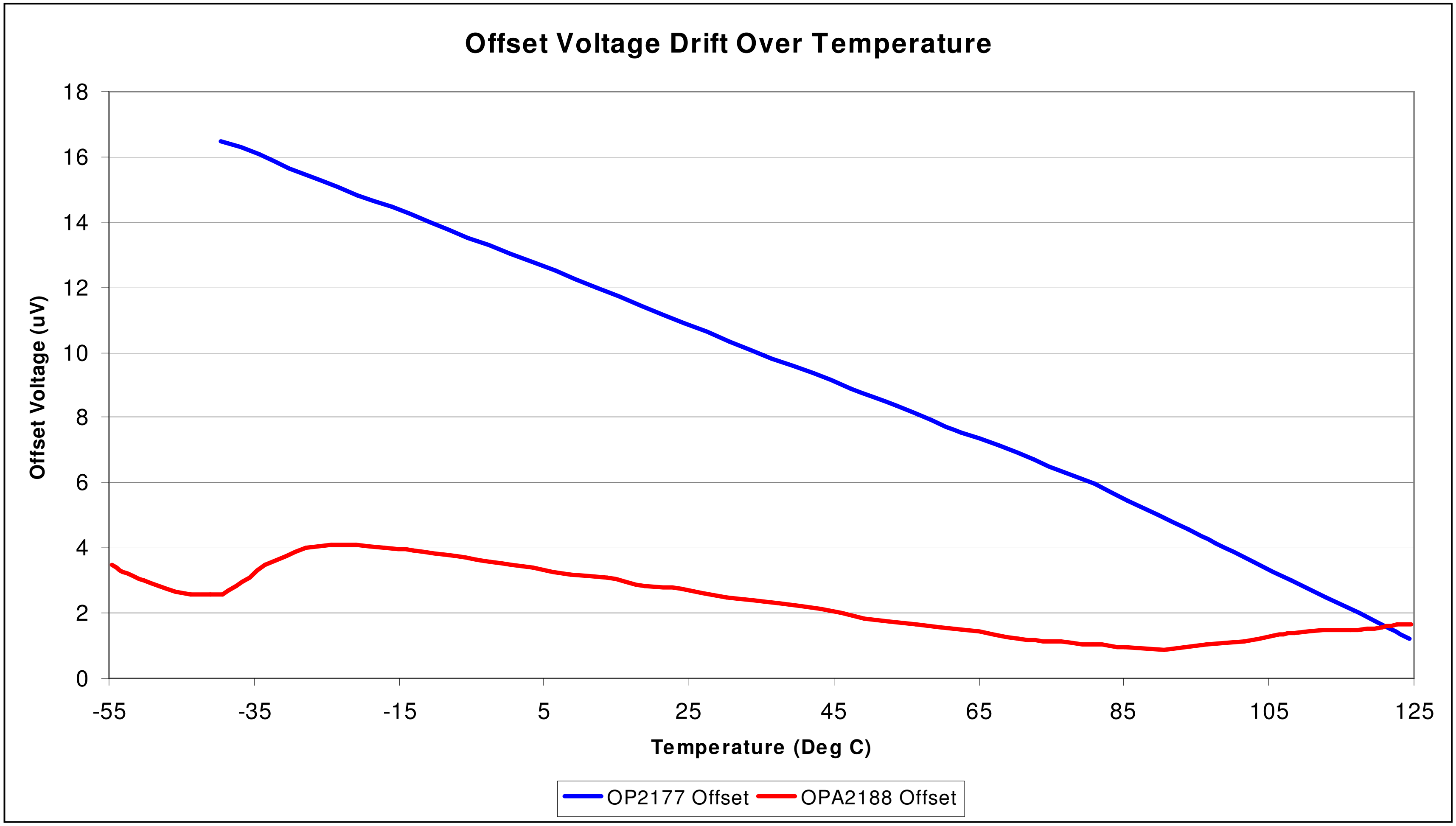
## Advantages

- Low Vos
- Low Vos Drift
- Good CMRR
- Good PSRR
- Good long term drift
- Better Insensitivity to stress, moisture
- No 1/f noise
- Better EMI Immunity

## Drawbacks

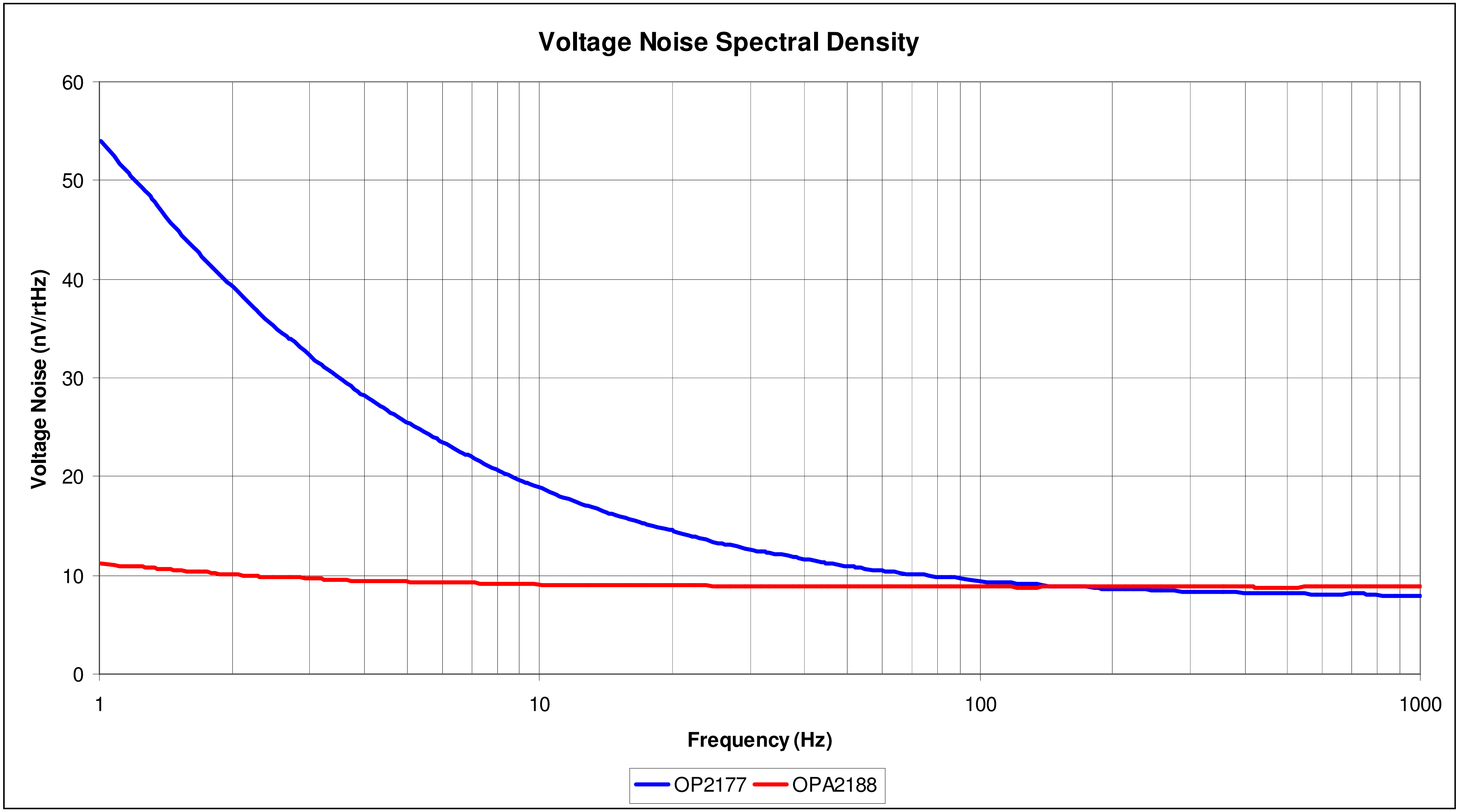
- Chopper / Auto-Zero feed-through
- Higher Ib
- Transient IB noise

# Offset Drift Comparison



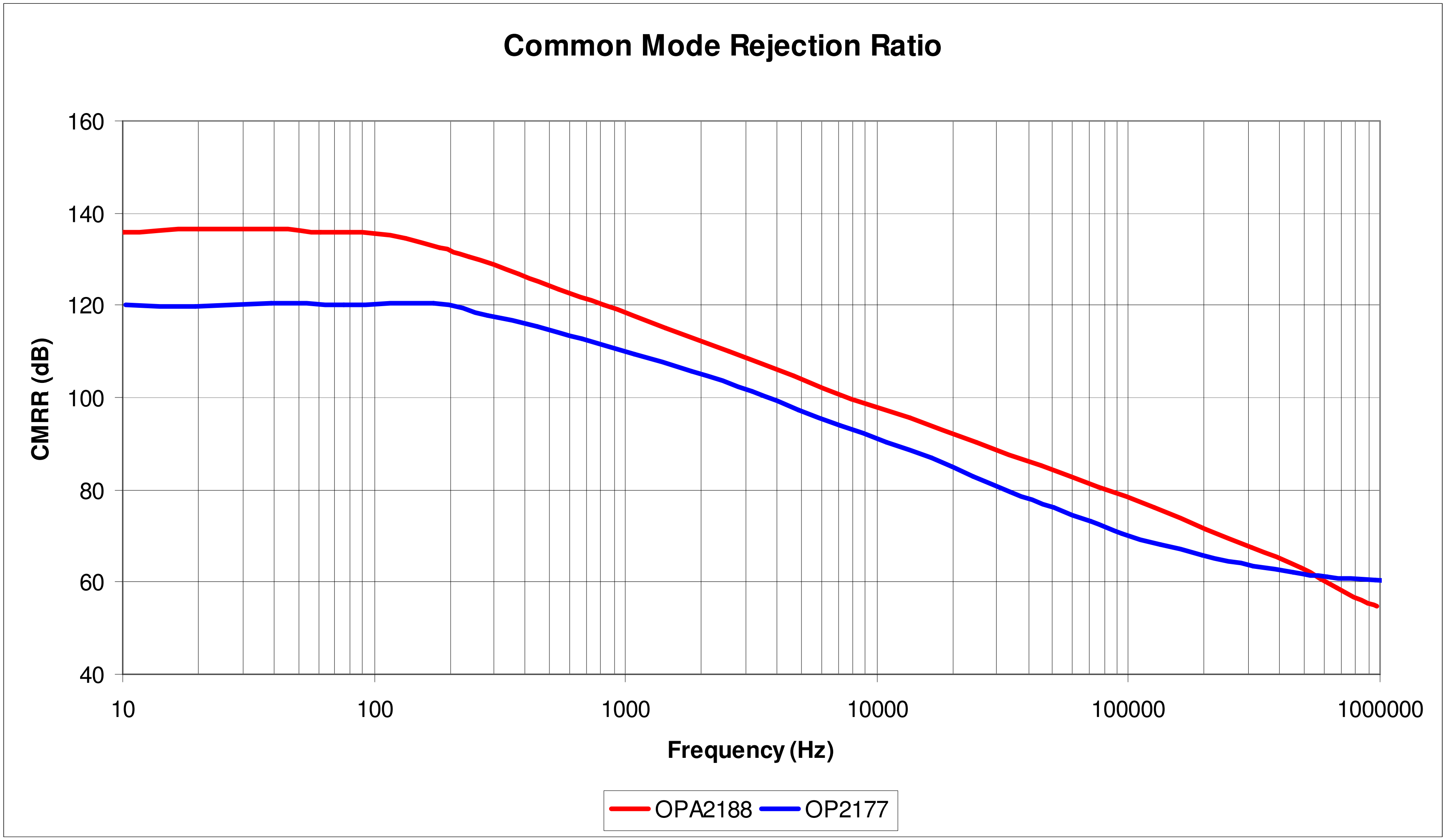

- Offset drift comparison between the OPA2188 and the OP2177
  - OP2177 (blue trace) .2uV/ºC typical
  - OPA2188 (red trace) .03uV/ºC typical
- Chopping allows the OPA2188 to reduce offset drift over temperature by almost 7x

# Low Frequency Noise Comparison



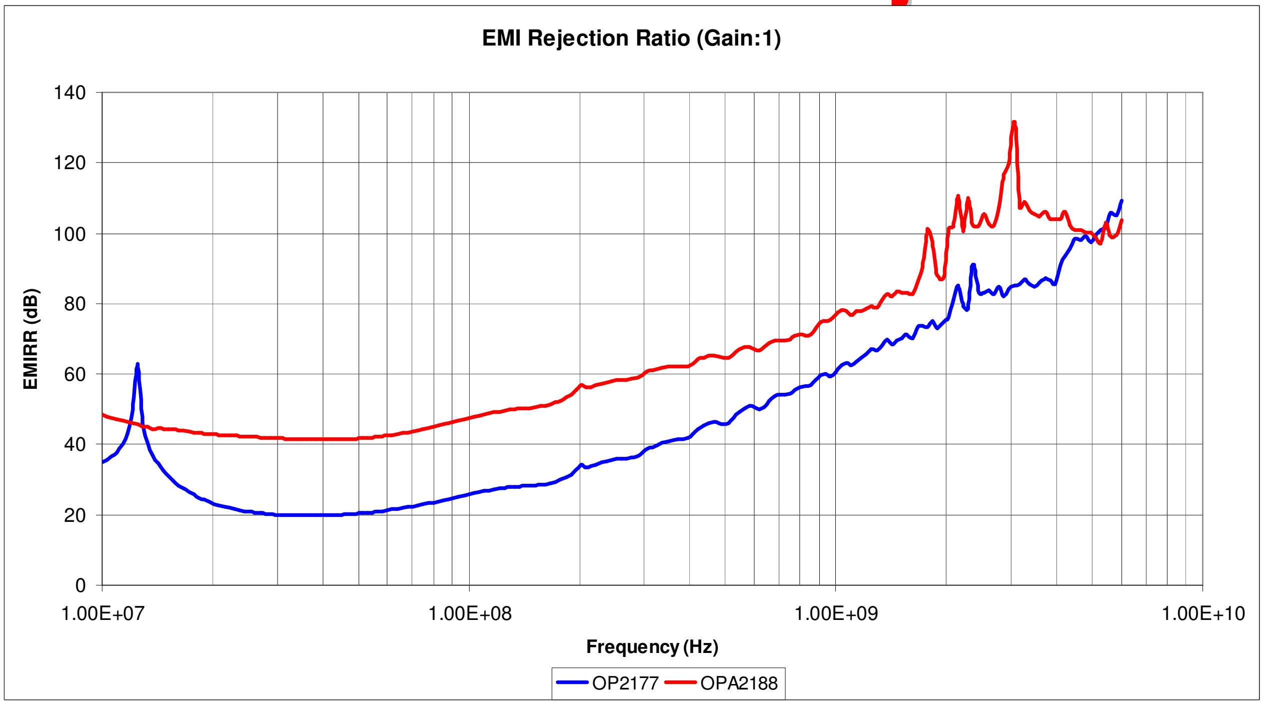

- Low-frequency noise comparison between the OPA2188 and the OP2177
  - OP2177 (blue trace) 8nV/rtHz @1kHz → 54nV/rtHz @1Hz
  - OPA2188 (red trace) ~8.8nV/rtHz @ 1kHz → 11nV/rtHz @1Hz
- Below 100Hz the OPA2188 shows a clear advantage for low-noise precision systems

# Common Mode Rejection Ratio

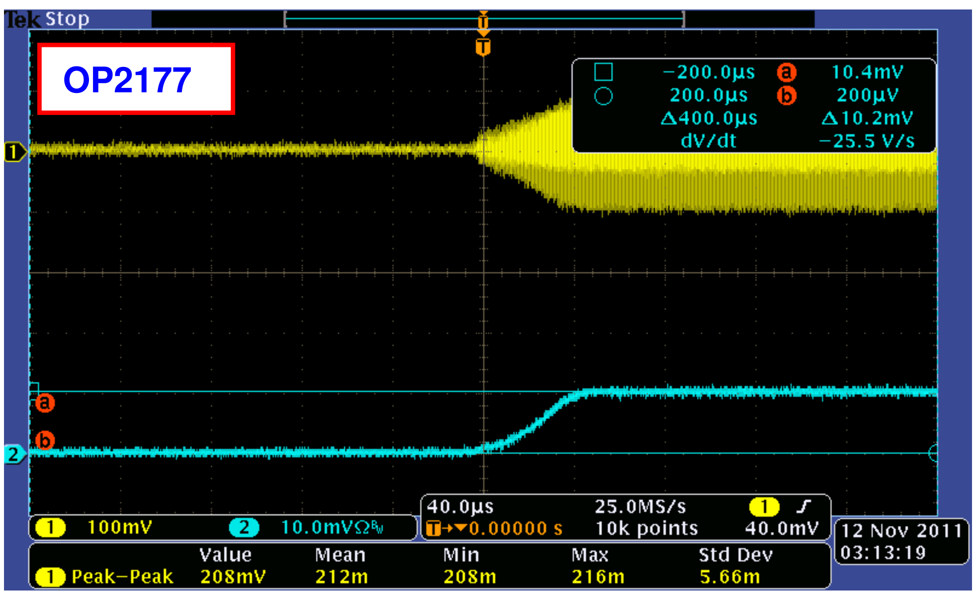


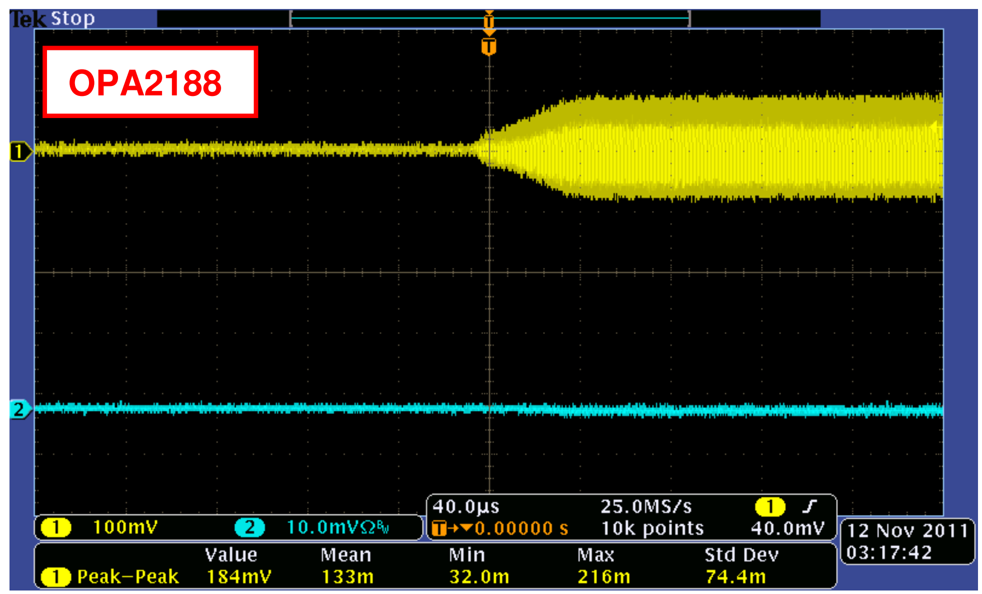

- Common-mode rejection ratio comparison between the OPA2188 and the OP2177
  - OP2177 (blue trace) 125dB typical
  - OPA2188 (red trace) 134dB typical

# EMI Rejection Ratio




- Rectification of EMI in the input differential pair produces additional DC offset
- Screenshots below show the change in offset (blue trace) due to input EMI (yellow trace)
  - OP2177 on left
  - OPA2188 on right



# What This Means to Our Customers

- Better Initial Accuracy
  - Improved initial offset
- Better performance in harsh environments
  - Improved rejection of ground/CM noise
  - Improved rejection of EMI
- Fewer recalibrations
  - Greatly reduced drift over time and temperature

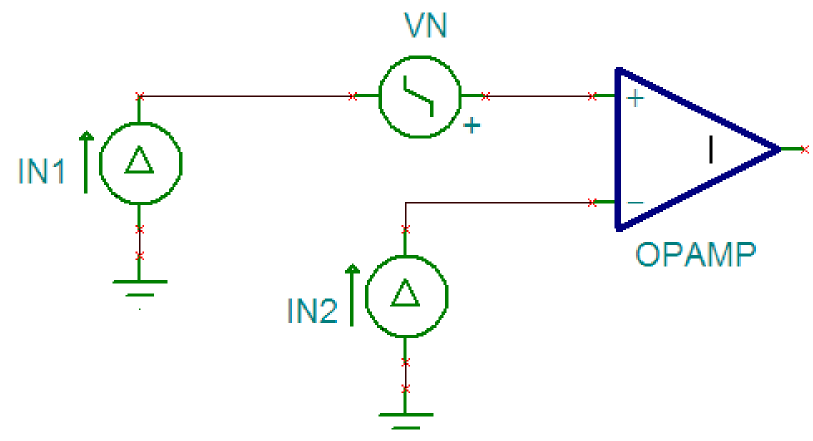
# Chopper Op Amp Intrinsic Noise Sources

Noise sources in standard op amps

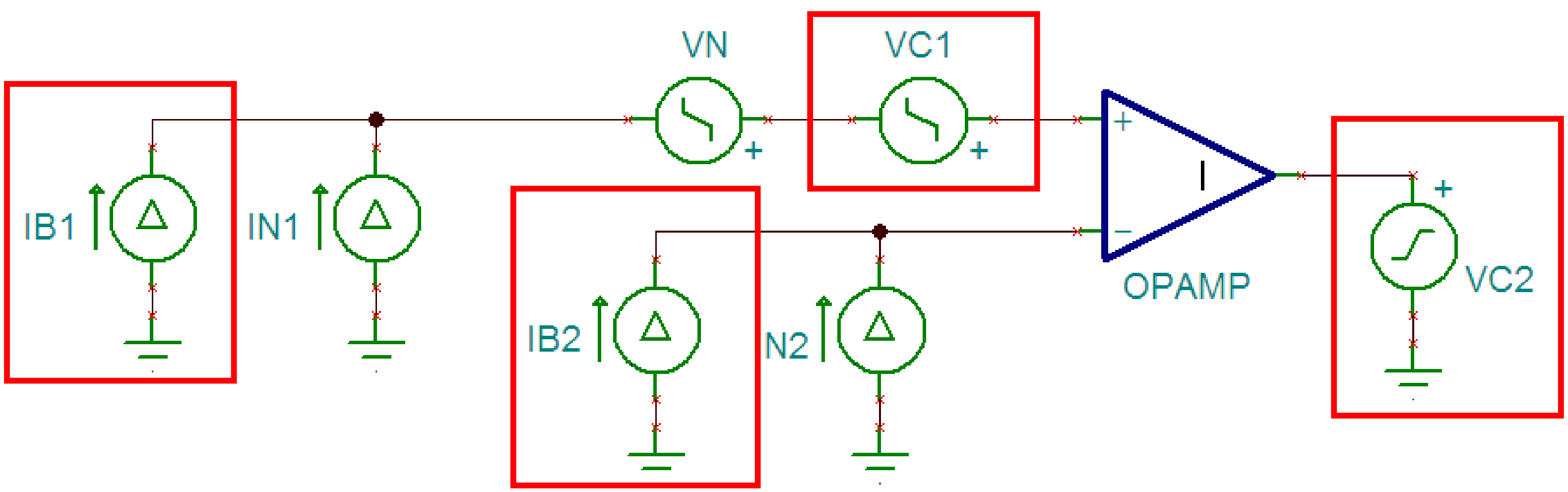
- Input Current Noise (IN1, IN2)
- Input Voltage Noise (VN)

Chopper amplifiers have additional noise sources that should be considered in system design

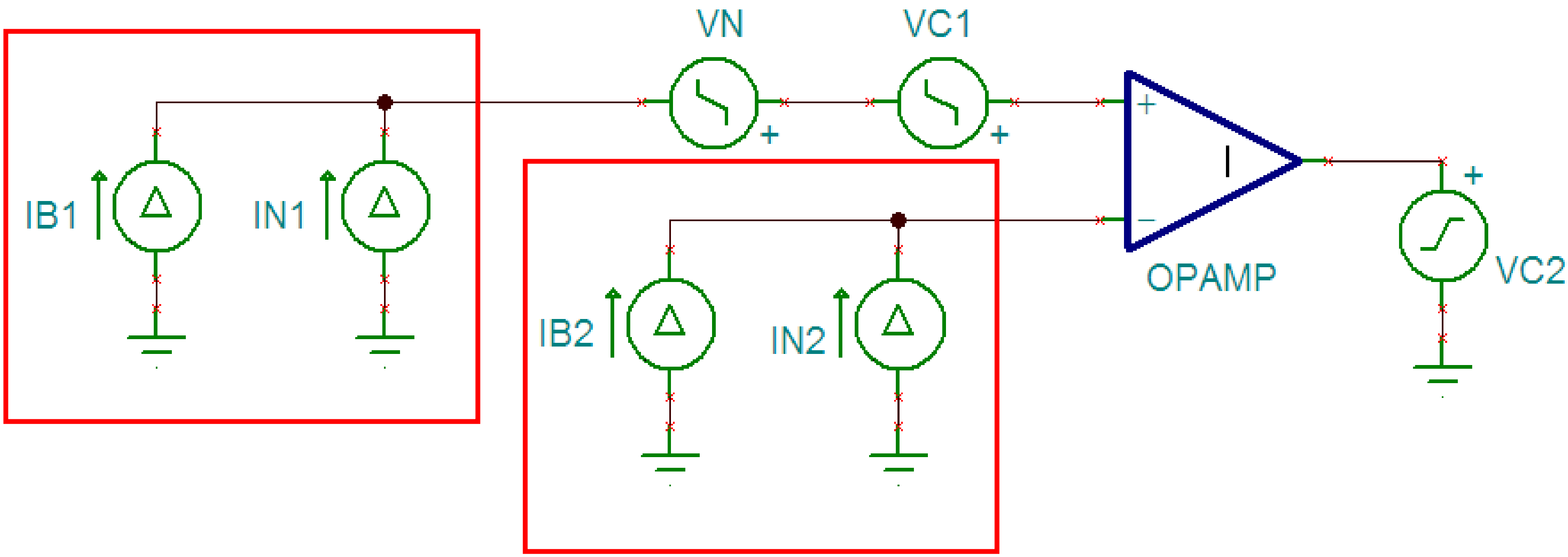
- Input bias current transients (IB1, IB2)
- Chopper clock feed-through
  - VC1 (input referred when chopping in-bandwidth)




Standard Op Amp Noise Sources



# Input Current Noise




- Current noise on the inputs can be broken into two separate sources
  - Standard input current noise (IN1, IN2)
    - Gaussian distribution
    - Present in all opamps
  - Transient bias current noise (IB1, IB2)
    - Periodic/repetitive
    - Present in devices with input commutation

# FET-Input Op Amp Current Noise

- Broadband current noise in FET Input Op Amps can be calculated from the input bias current:

$$i_n = \sqrt{2 * q * i_B}$$

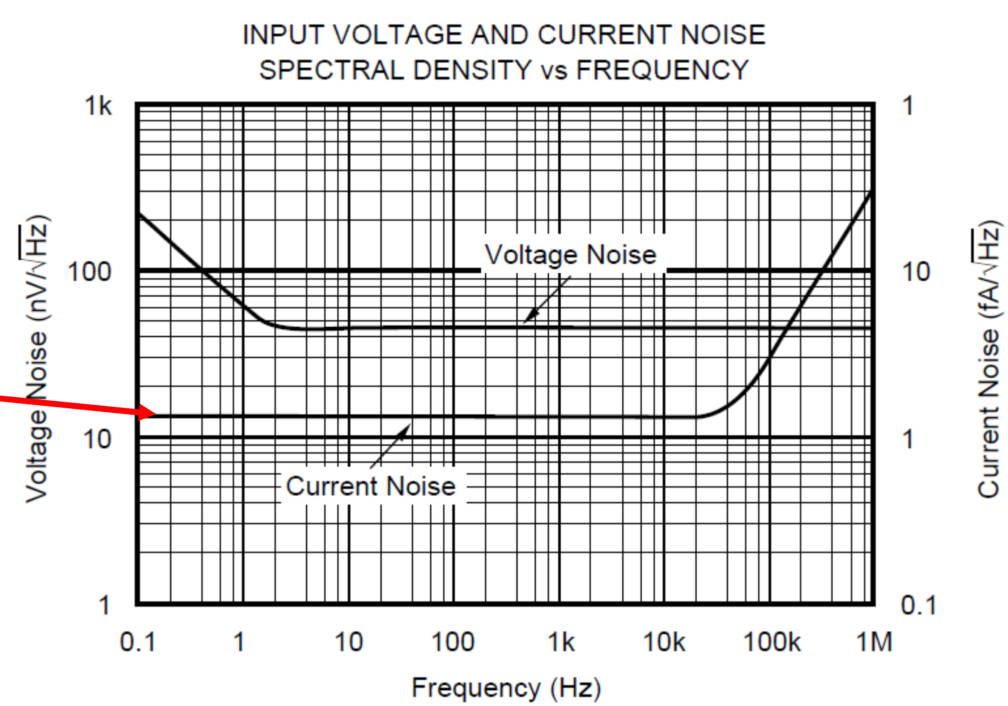
| | | | |
|---|---|---|---|
| Input Bias Current | $I_B$ | ±5 | pA |
| **NOISE** | | | |
| Input Voltage Noise, f = 0.1 to 10Hz | | 2 | μVp-p |
| Input Voltage Noise Density, f = 1kHz | $e_n$ | 45 | nV/√Hz |
| Current Noise Density, f = 1kHz | $i_n$ | 1.2 | fA/√Hz |

$i_n$: Current Noise Spectral Density

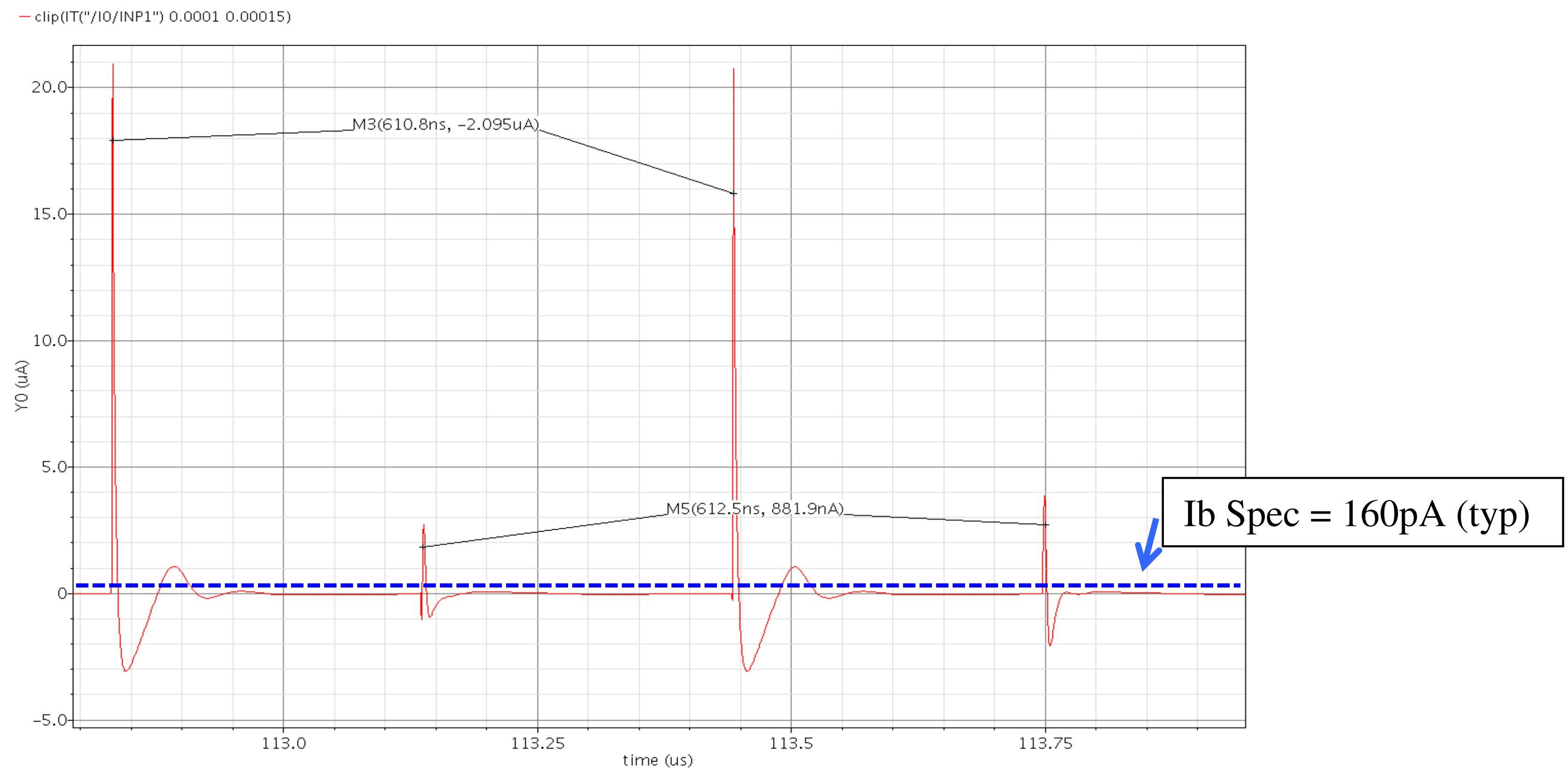
*Q*: Charge of an electron (1.6x10$^{-19}$ Coulombs)

$i_B$: Input Bias Current

$$i_n = \sqrt{2 * 1.6 \times 10^{-19} * 5 \times 10^{-12}} = 1.26 fA / \sqrt{Hz}$$



# Chopper Input Bias Current is NOT a constant!

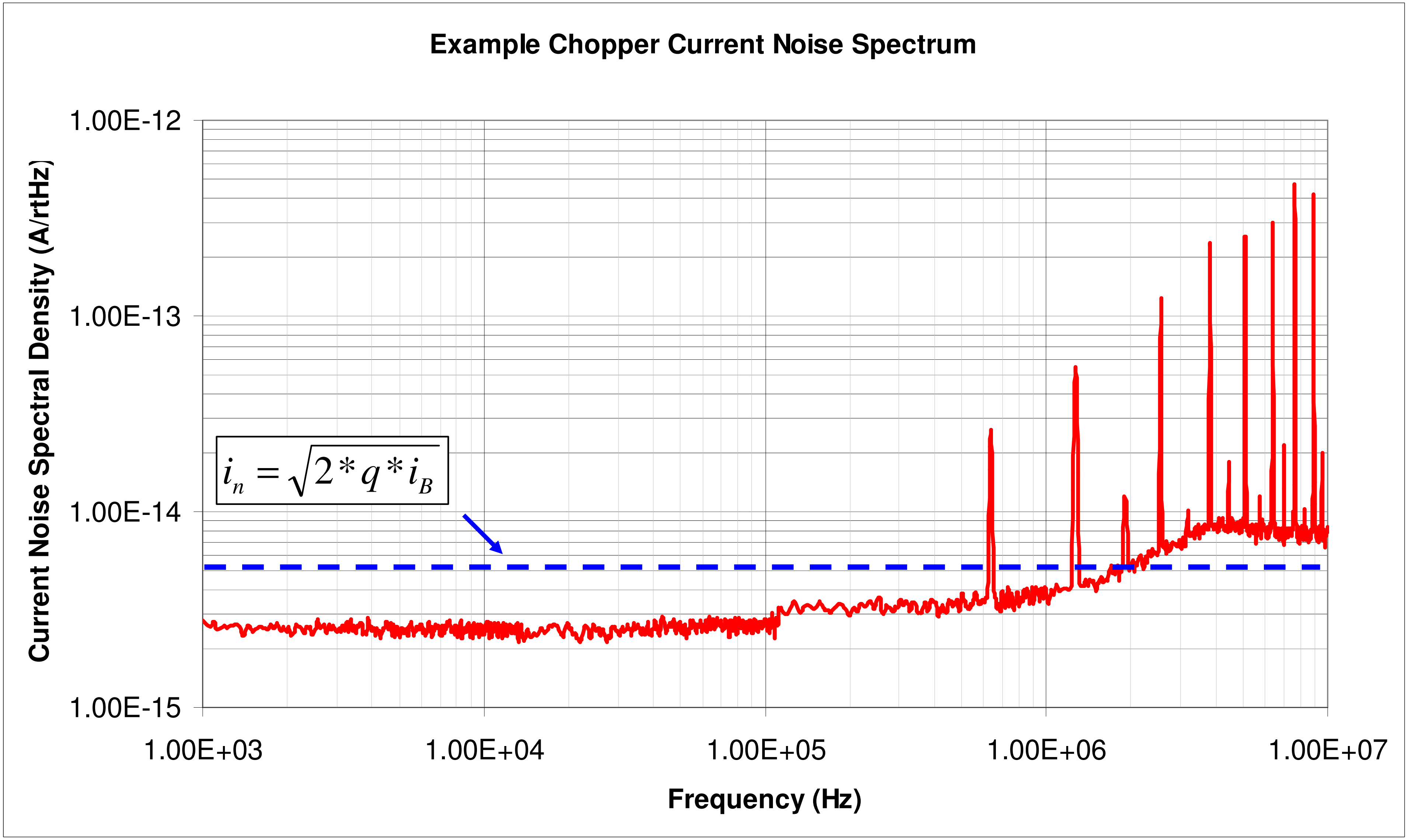



Chopper input bias current is actually a periodic waveform consisting of:

- An offset current (actual IB of input circuitry)
- A periodic current waveform from switching

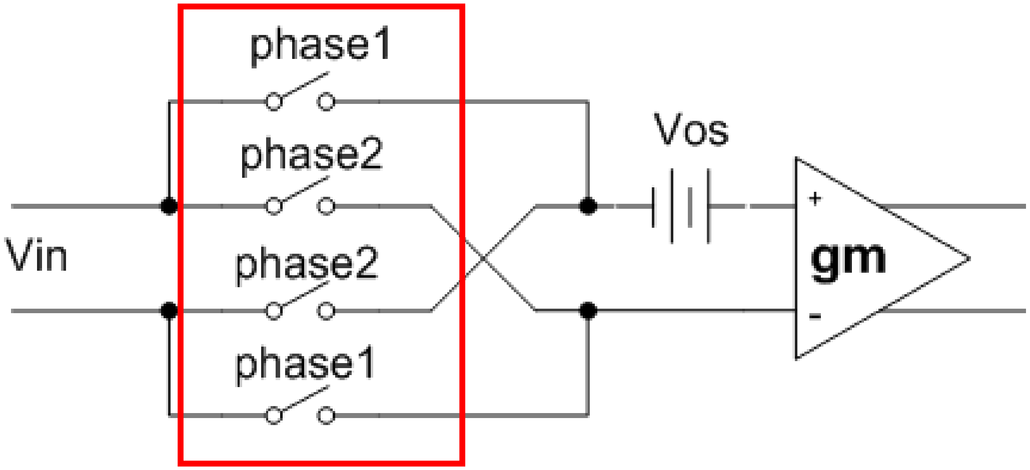
The IB spec in the datasheet is determined by averaging the combination of these two values over a long period of time

# Chopper Current Noise in the Frequency Domain




The current noise spectral density spec is only valid, yet pessimistic, below the chopping frequency

# What causes the Ib spike?




**Charge Injection**

• When the transistor turns off, the channel charge is dispersed into the source and drain

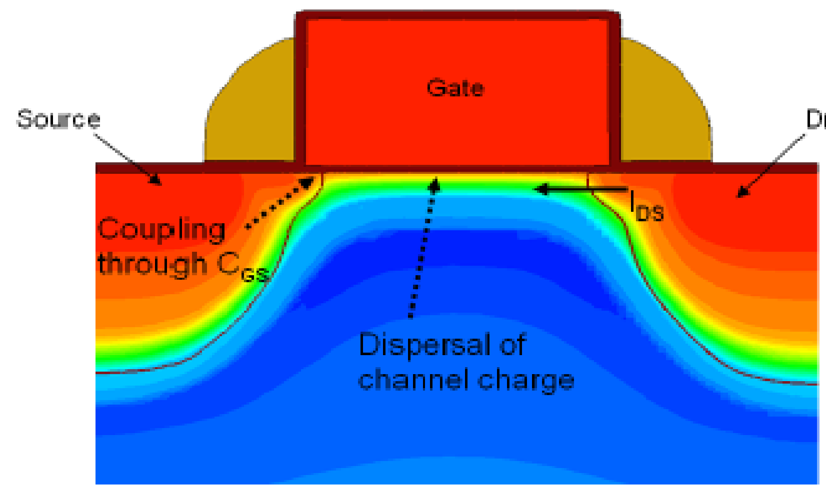
• $Q_{ch} = C_{ox} (V_{gs} – V_t)$

$dV_{Qch} = Q_{ch} / 2C_s$

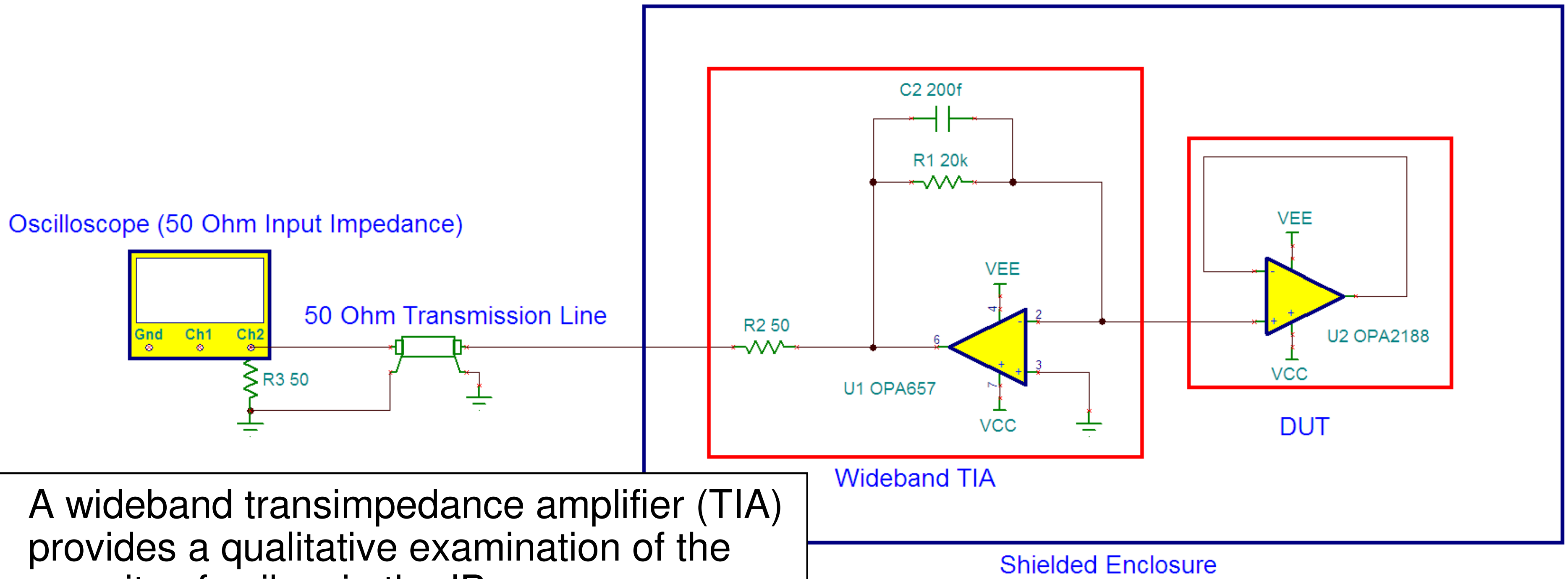
**Clock Feedthrough**

• When the transistor turns off, the source voltage is also affected due to the coupling from gate-source capacitance

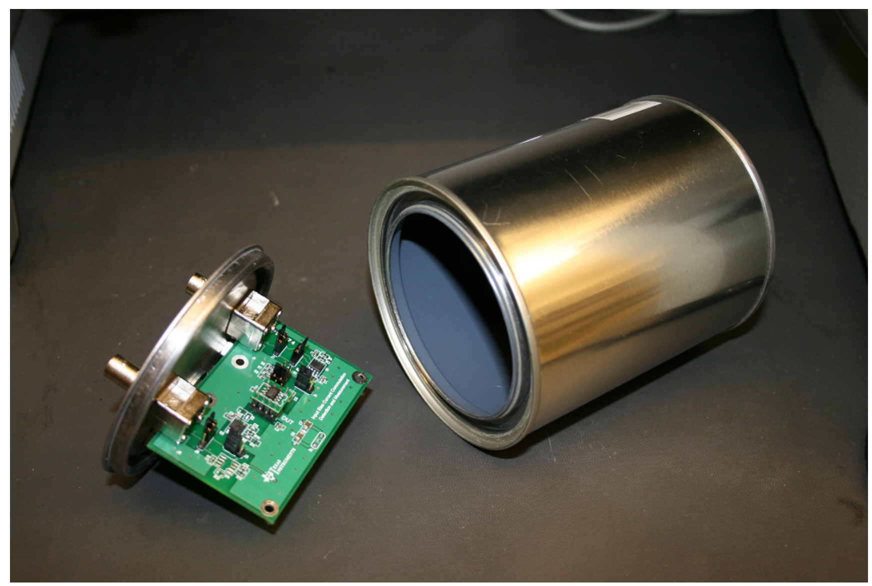
$$\Delta V_{Col} = \Delta V_G * \frac{C_{GS}}{C_{GS} + C_S}$$



# Observing Bias Current Spikes



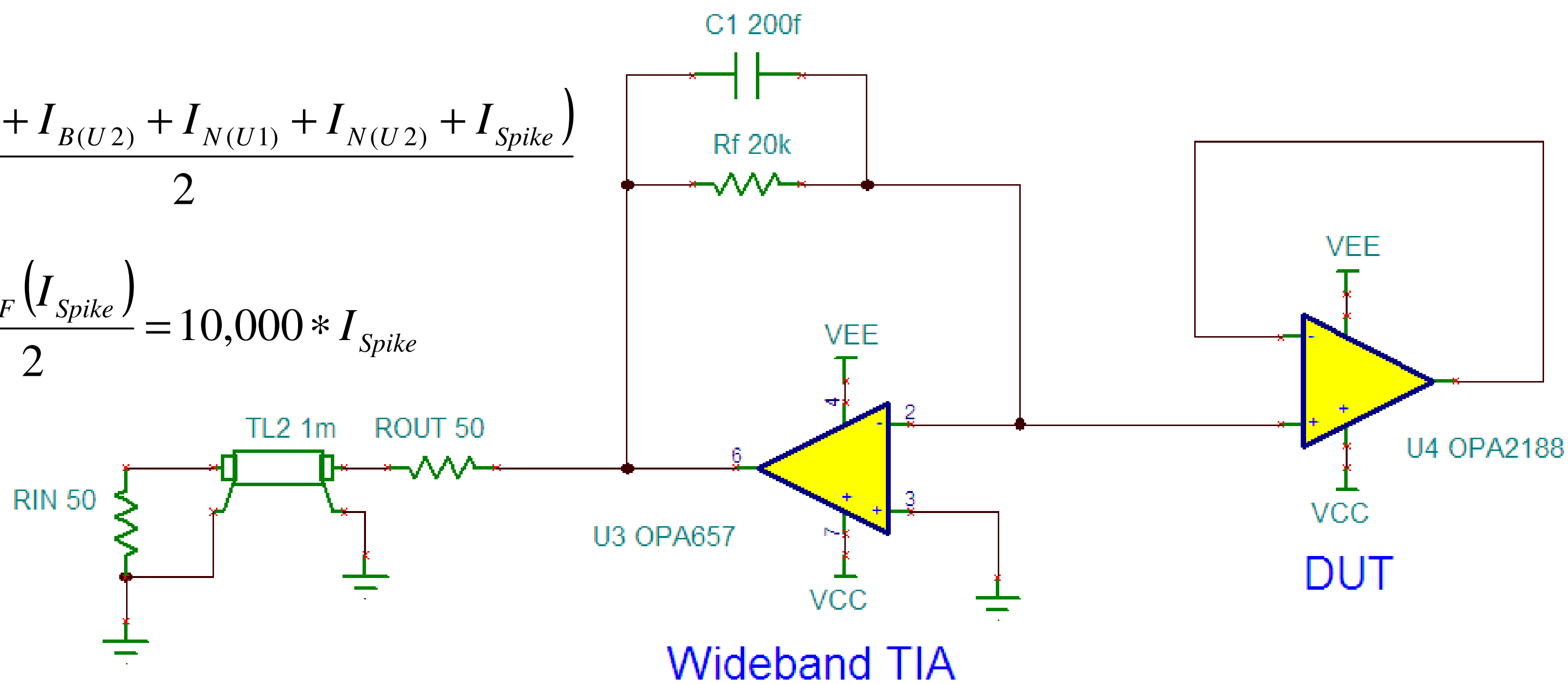

- A wideband transimpedance amplifier (TIA) provides a qualitative examination of the severity of spikes in the IB
  - The chopper is configured as a buffer
  - Non-inverting input is connected directly to the TIA input
- Testing was performed with an OPA657 configured for a gain of 20,000
  - Final gain is 10,000 after impedance matching
  - Output viewed on a 500MHz oscilloscope (50 ohm input)



# Observing Bias Current Spikes

$$V_{OUT} = \frac{-R_F\left(I_{B(U1)} + I_{B(U2)} + I_{N(U1)} + I_{N(U2)} + I_{Spike}\right)}{2}$$

$$V_{OUT} \approx \frac{-R_F\left(I_{Spike}\right)}{2} = 10{,}000 * I_{Spike}$$



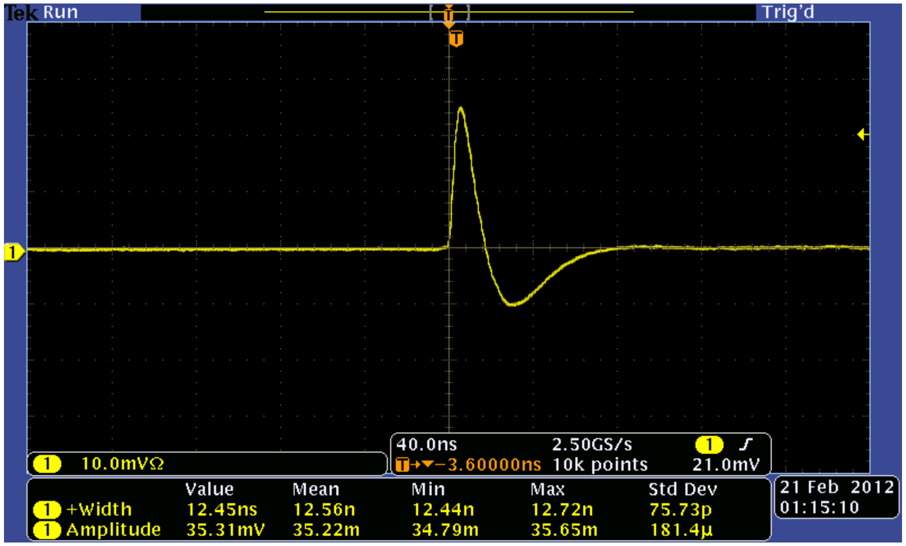

- Static IB should appear as a DC offset
- Averaging on the oscilloscope can be used to remove Gaussian current noise
- Any repetitive signal in the bias current should dominate the averaged output waveform

| | OPA657 | OPA2188 |
|---|---|---|
| Bias Current | 2 pA | 160 pA |
| Current Noise | 1.3 fA/rtHz | 7 fA/rtHz |

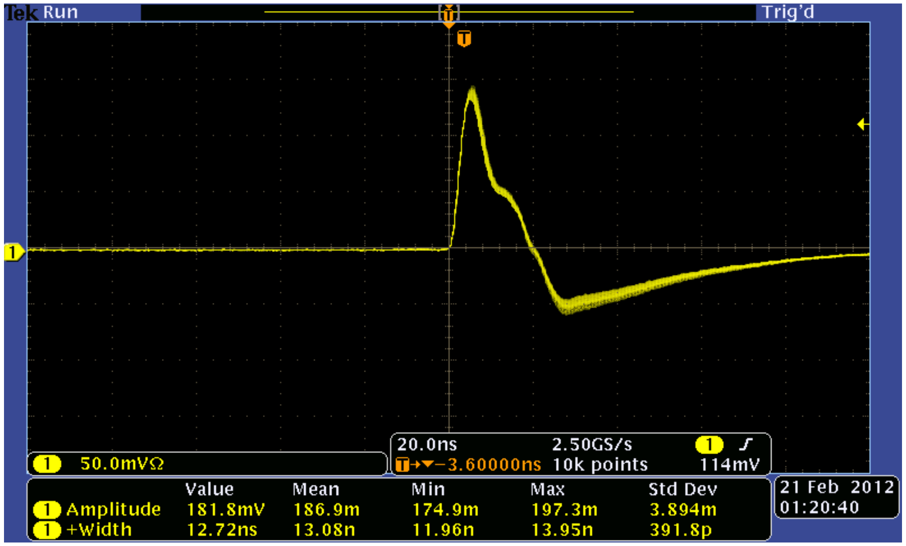
$$f_{-3dB} = 60MHz$$

# Investigation Results

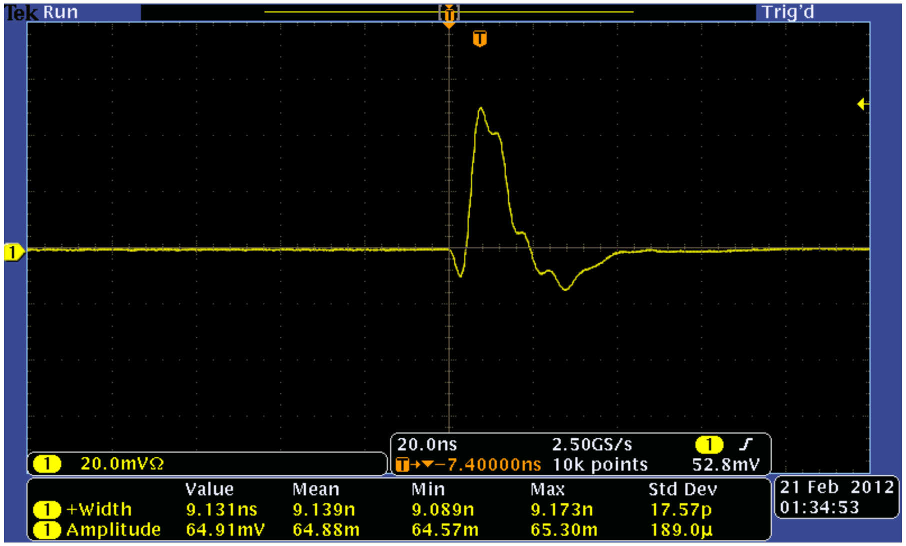
- Chopper amplifiers from TI and two competitors were examined
  - OPA2188
  - AD8639
  - MAX44251
- All parts exhibited similar behavior at the inputs
- Very good correlation between IC-level simulation and observed behavior
  - Improvement in future designs




OPA2188

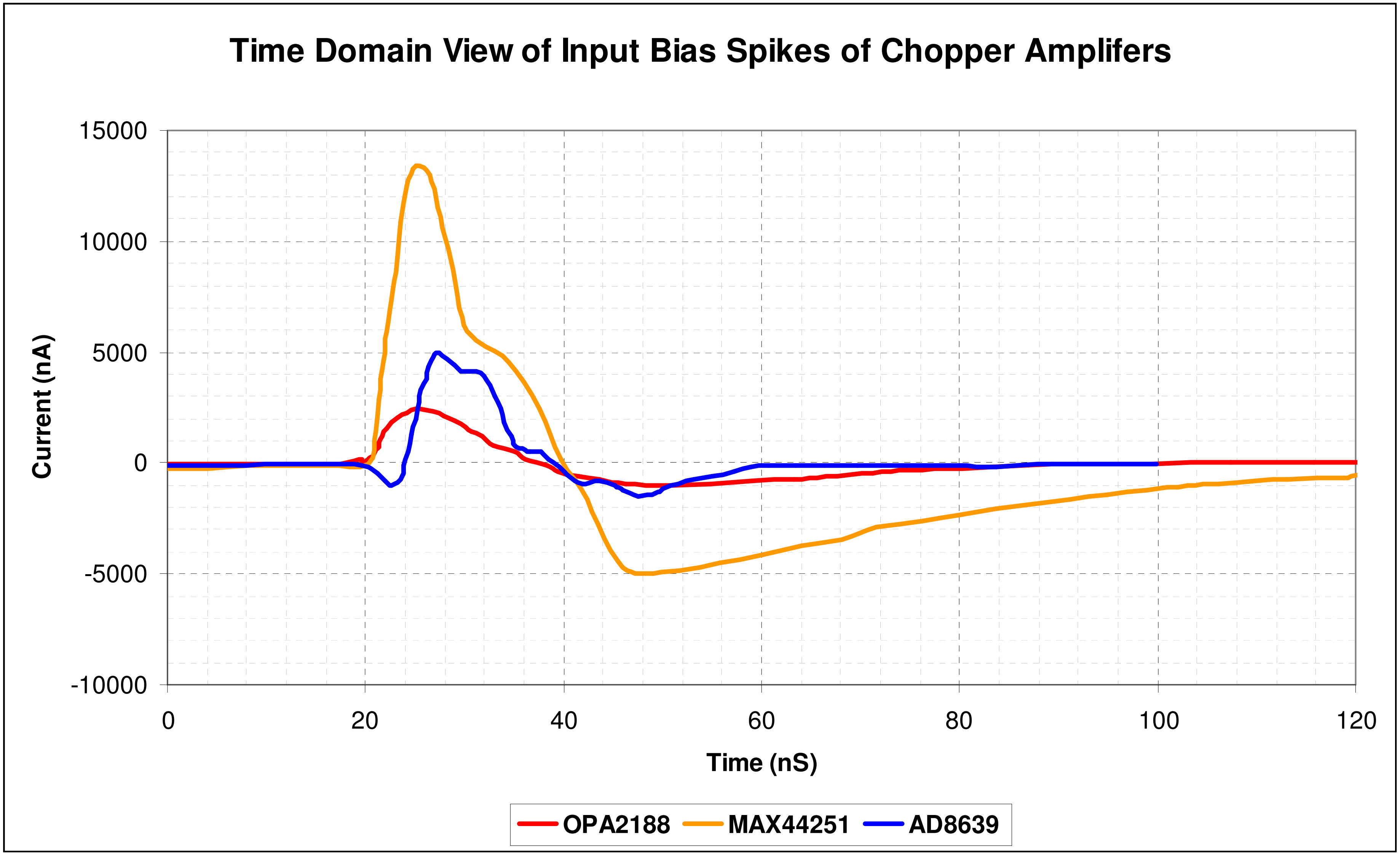



MAX44251




AD8639

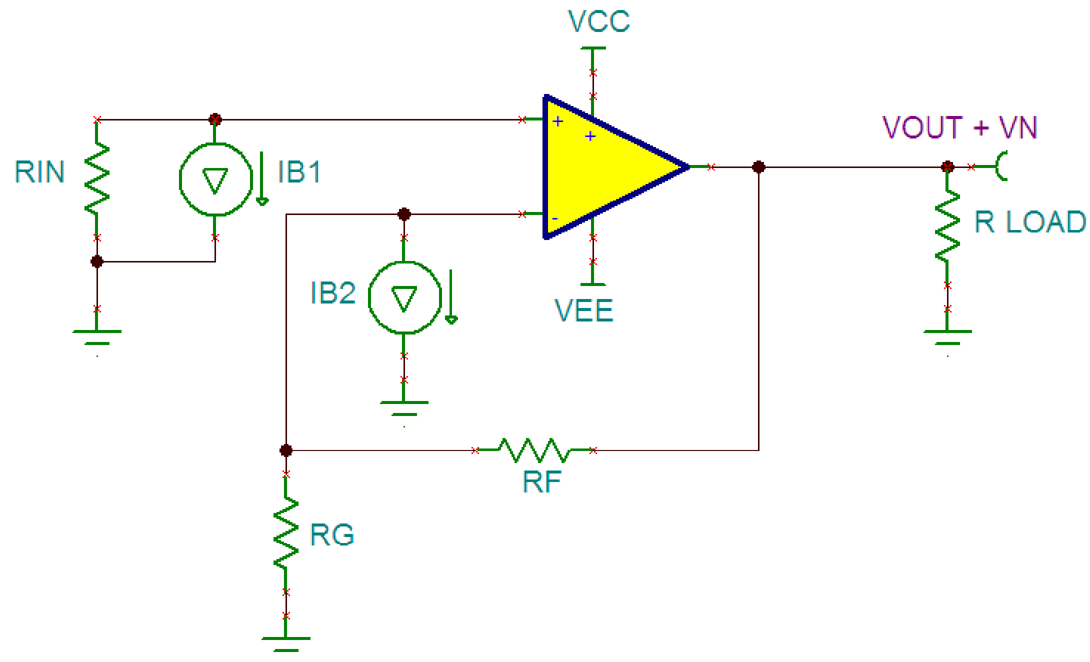
# Comparison to Competitor Chopper Amplifiers

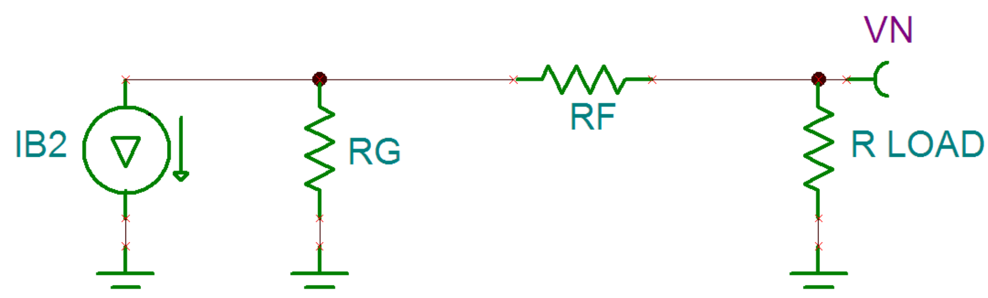



- Overlaying the input bias spike waveform in the time domain allows for a direct comparison
  - The OPA2188 has the least severe input bias spike of the parts examined
  - The MAX44251 displayed the worst performance

# Effects on System Performance

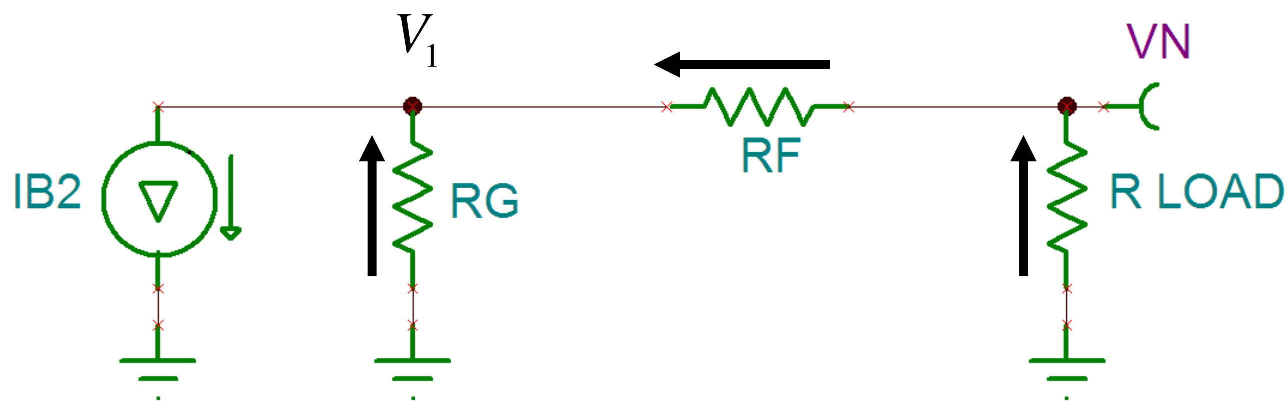
- Input current spikes are outside the opamp bandwidth
- Spikes on the Non-Inverting Input:
  - Not amplified
  - May affect high-impedance sensors (sensor becomes transducer)
- Spikes on the Inverting Input:
  - Not amplified
  - The opamp can be removed to simplify analysis of the noise contribution
  - Current noise is coupled to the load through the feedback network



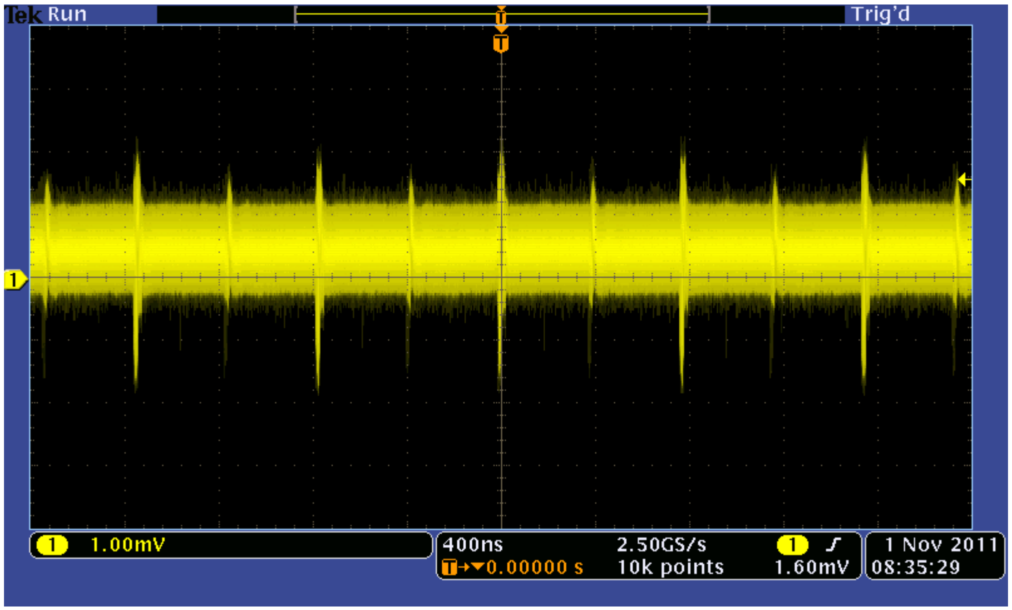
# Contribution to Output Noise

Current spikes on the inverting input are coupled to the load by the feedback network




$$V_1 = I_{B2}(R_G \| R_F + R_{LOAD})$$

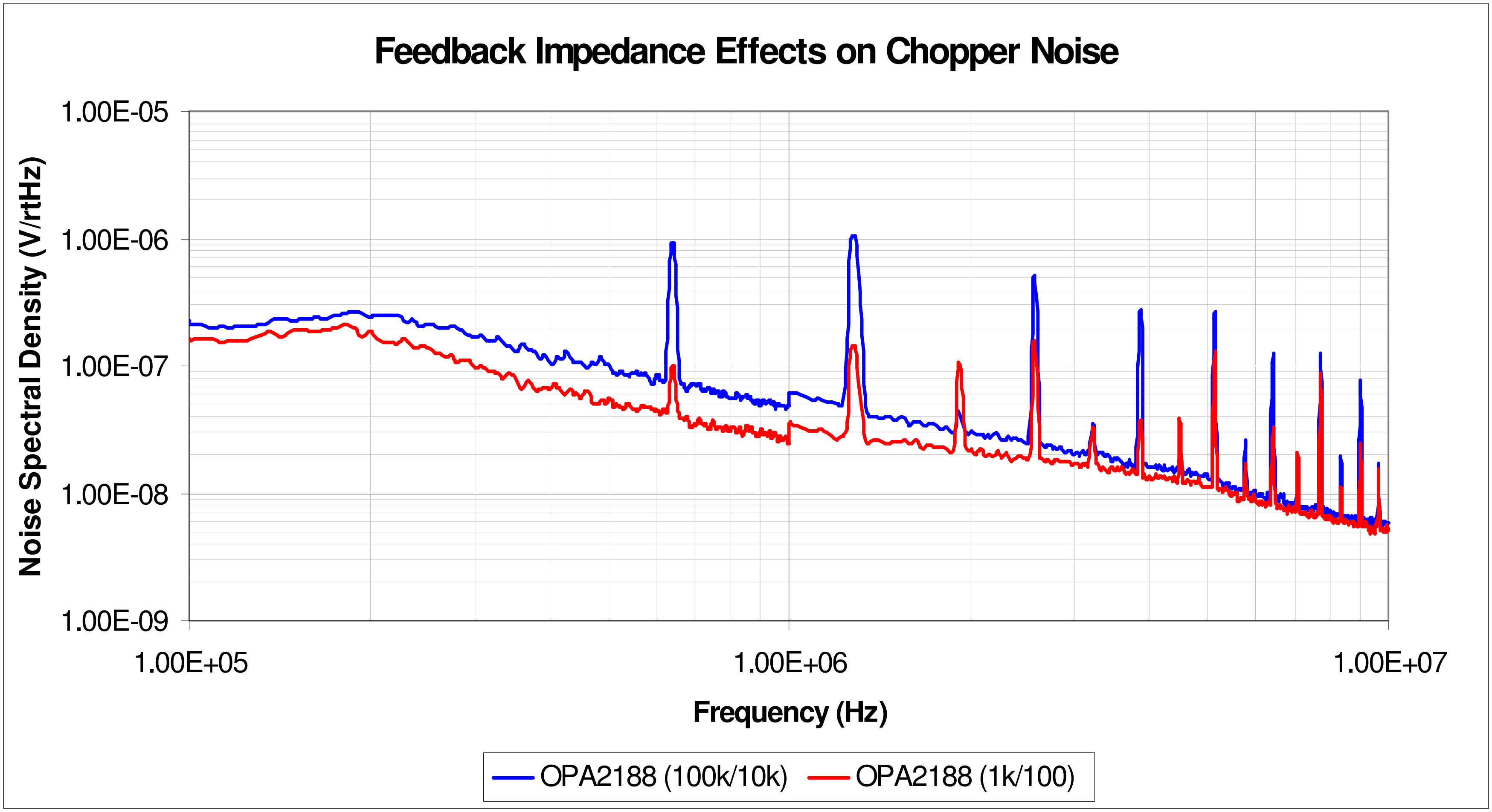
$$V_N = V_1 \frac{R_{LOAD}}{R_F + R_{LOAD}}$$




Output noise is dependant upon:

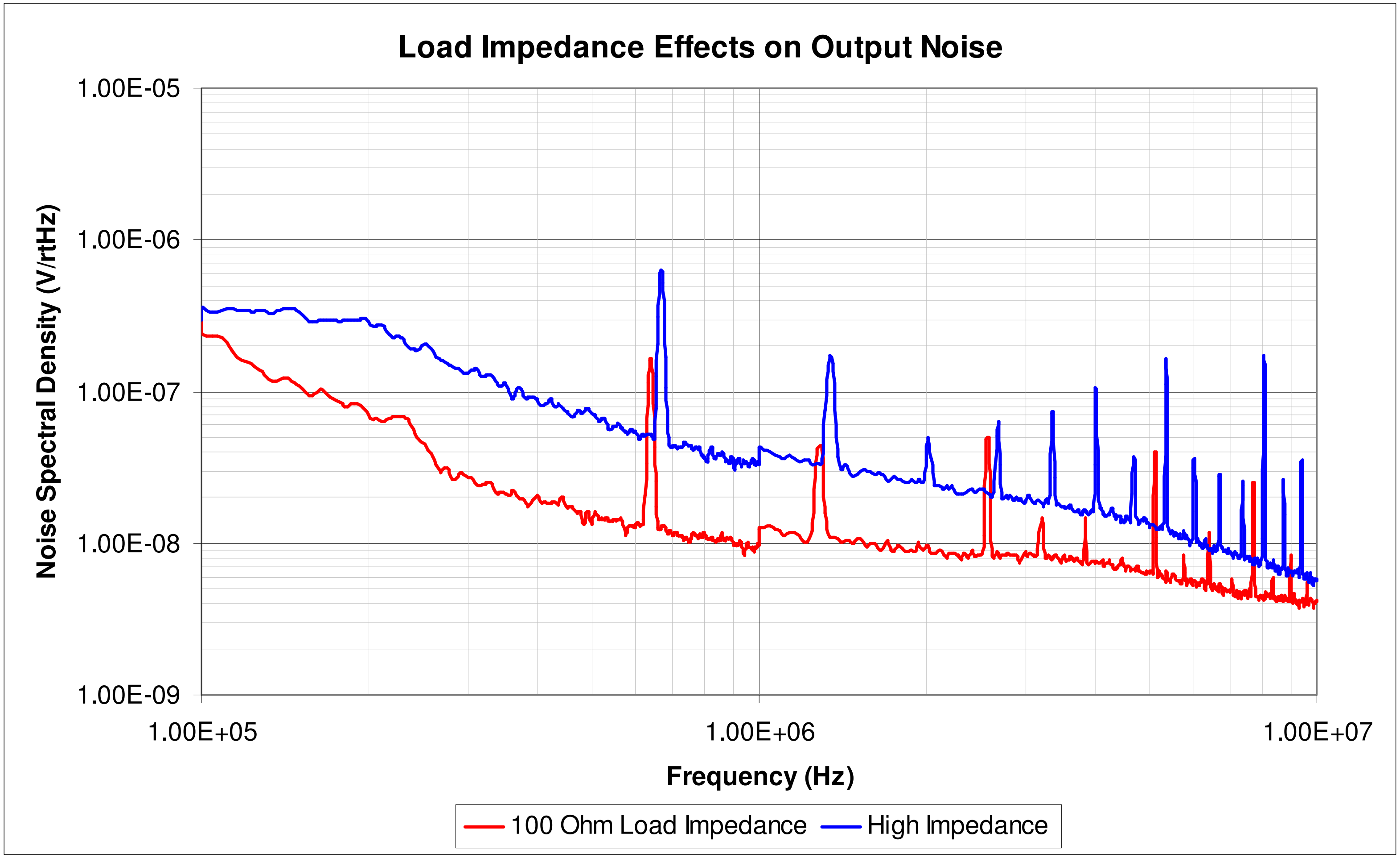
- Input current spike magnitude
- Feedback network impedance (RF and RG)
- Load Impedance (RLOAD)

# Feedback Network Impedance



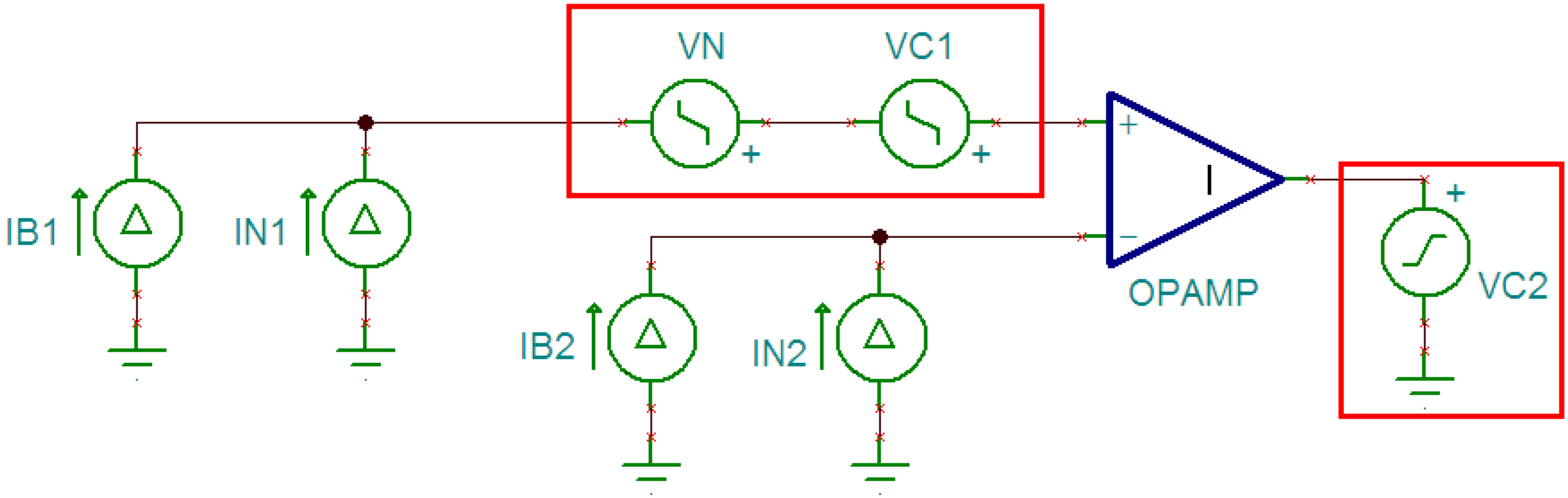

- Two OPA2188's were configured for a gain of 11
  - Blue trace → feedback values of 100kOhms and 10kOhms
  - Red trace → feedback values of 1kOhms and 100 Ohms
- Broadband noise reduction is expected from reduced thermal noise of resistances
- Reduction in chopper harmonics due to reduced contribution of transient current noise

# Load Impedance Effects




- This plot shows the output noise from the same amplifier circuit (OPA2188) into two different load impedances
  - Red trace is the output noise into a 100 Ohm load
  - Blue trace is the output noise into a very high impedance load (input impedance of OPA211)
- A reduction in the magnitude of the chopper spurs is evident on the low impedance load

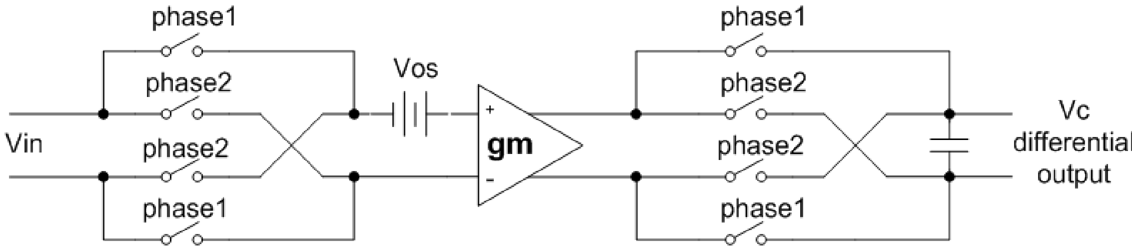
# Input and Output Voltage Noise



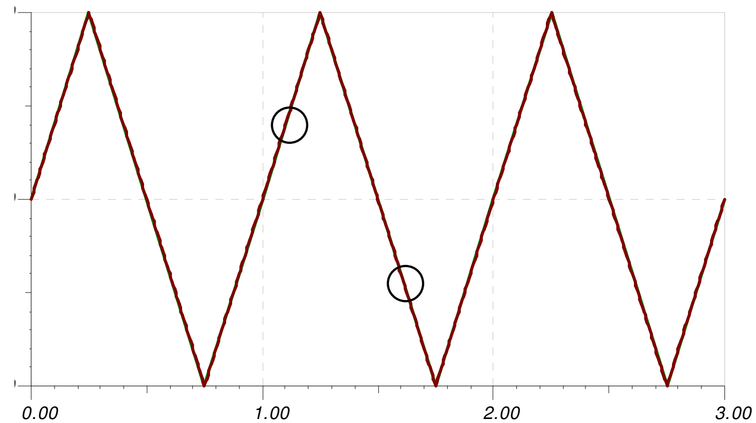

Voltage noise on the inputs can be broken into two or three separate sources

- Standard input voltage noise (VN)
  - Gaussian distribution
  - Present in all opamps
- Chopper clock feedthrough
  - Chopping within amplifier bandwidth → Input referred (VC1)
  - Chopping above amplifier bandwidth → Output referred (VC2)

# Chopper Voltage Noise




Time Domain




- The chopper topology modulates the input DC offset to an AC waveform with an average value of zero
- Symmetical charge and discharge of an output cap produces a triangle wave at the output
  - Consists of a fundamental (chopping frequency) and odd harmonics

Frequency Domain

# Synchronous Notch Filter

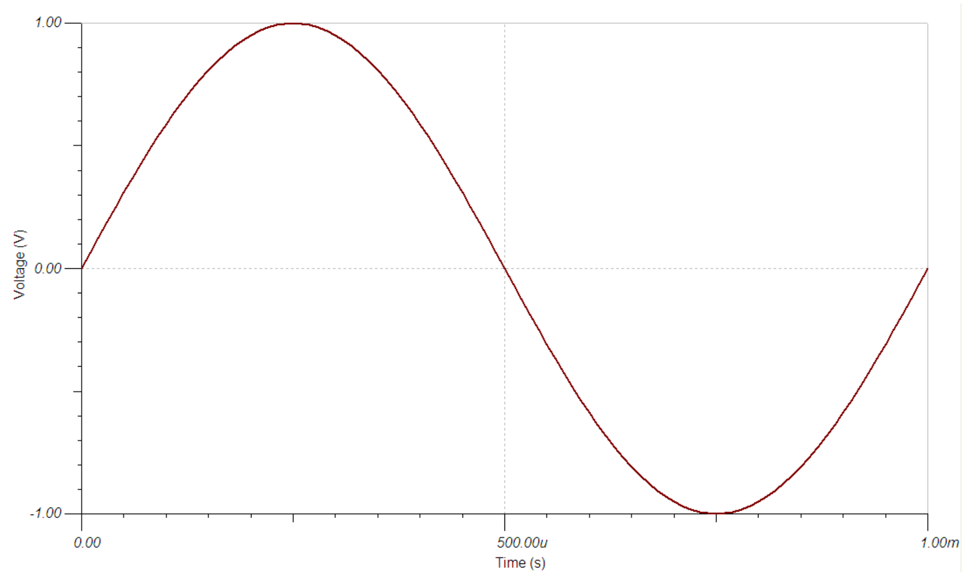
- Consider a repetitive waveform in the time domain
  - Zero offset
- The integral over one period of this waveform is zero

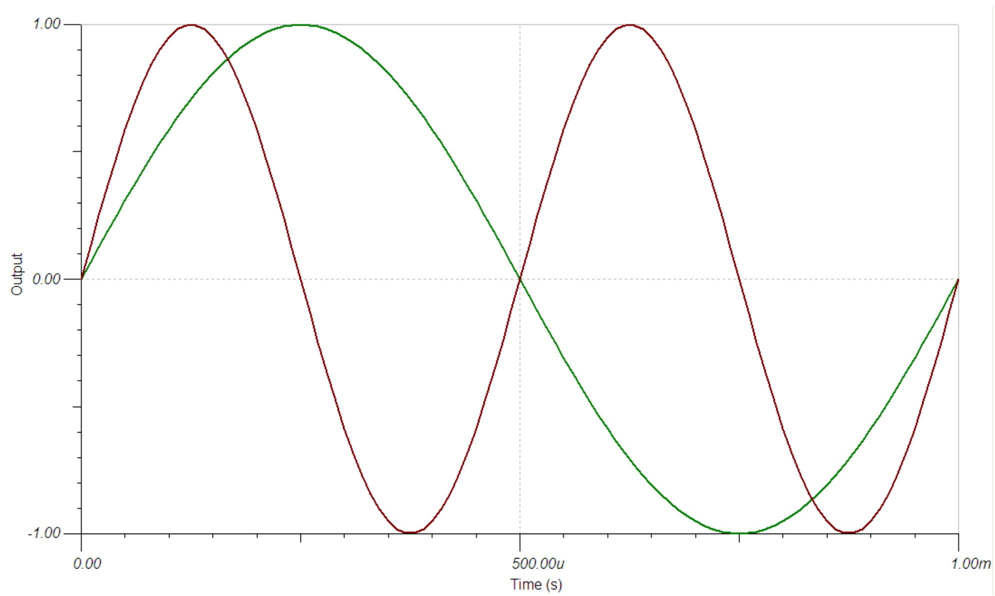
$$\int_T \sin(2\pi f t)dt = 0 \rightarrow T = \frac{1}{f}$$

- The integral will also be zero for the harmonics of this waveform
  - Integer multiples of frequency will also ingrate to zero over the same period

$$\int_T \sin(n * 2\pi f t)dt = 0 \rightarrow n = 1,2,3...$$

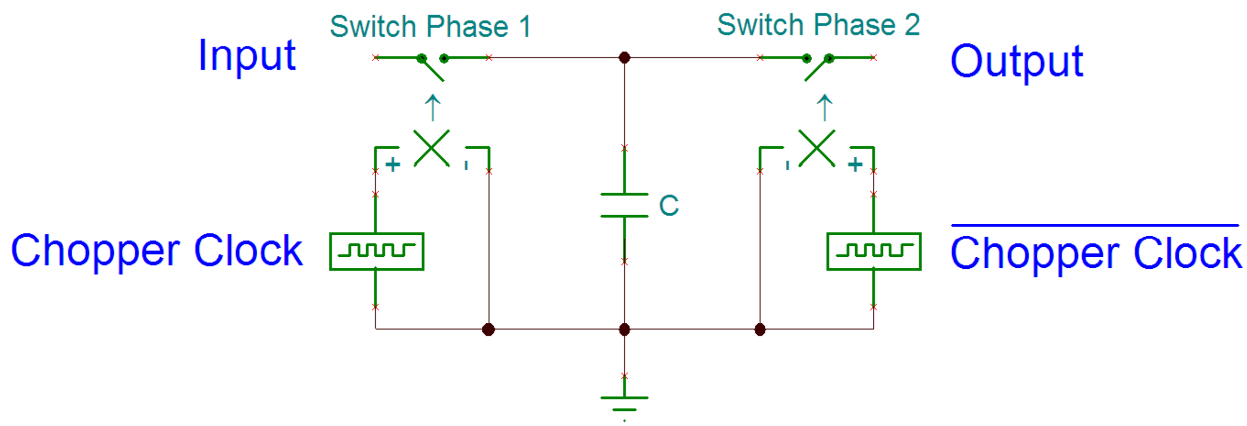
This concept allows us to build a filter with "notches" at integer multiples of frequency



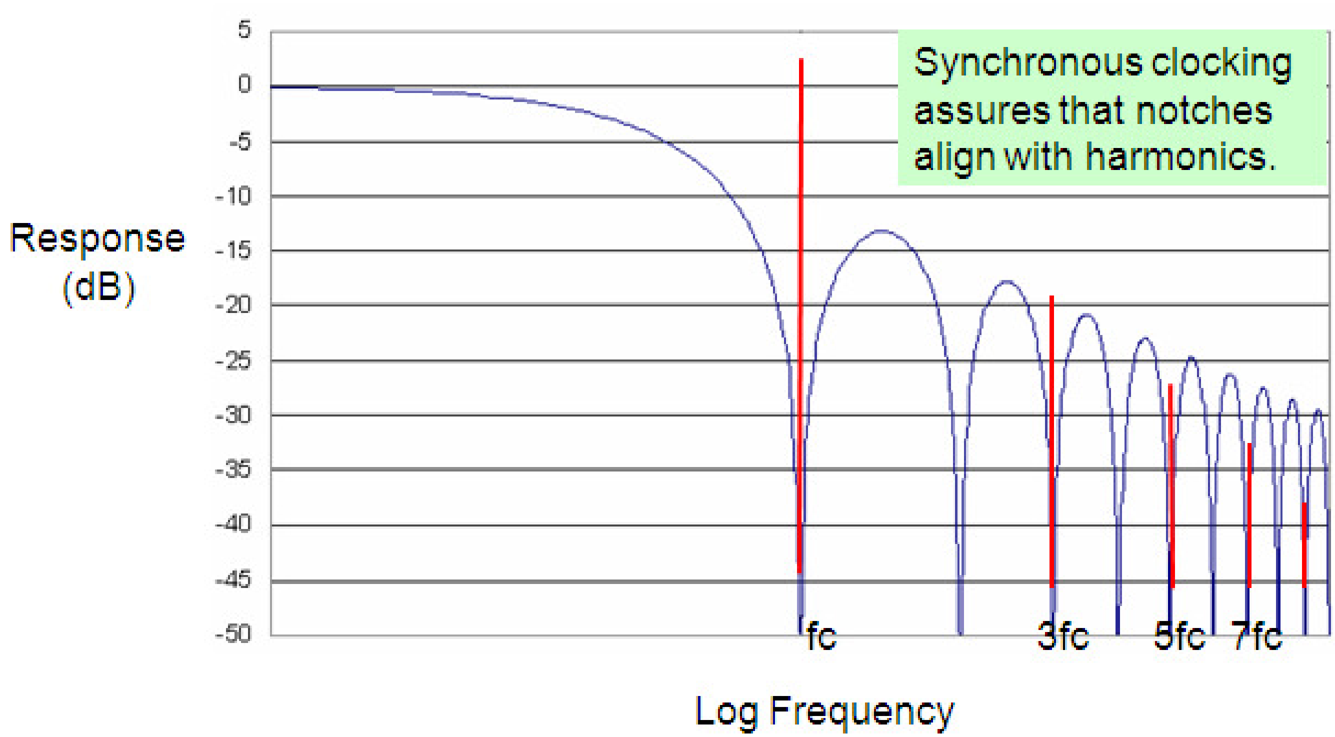



# Synchronous Notch Filter

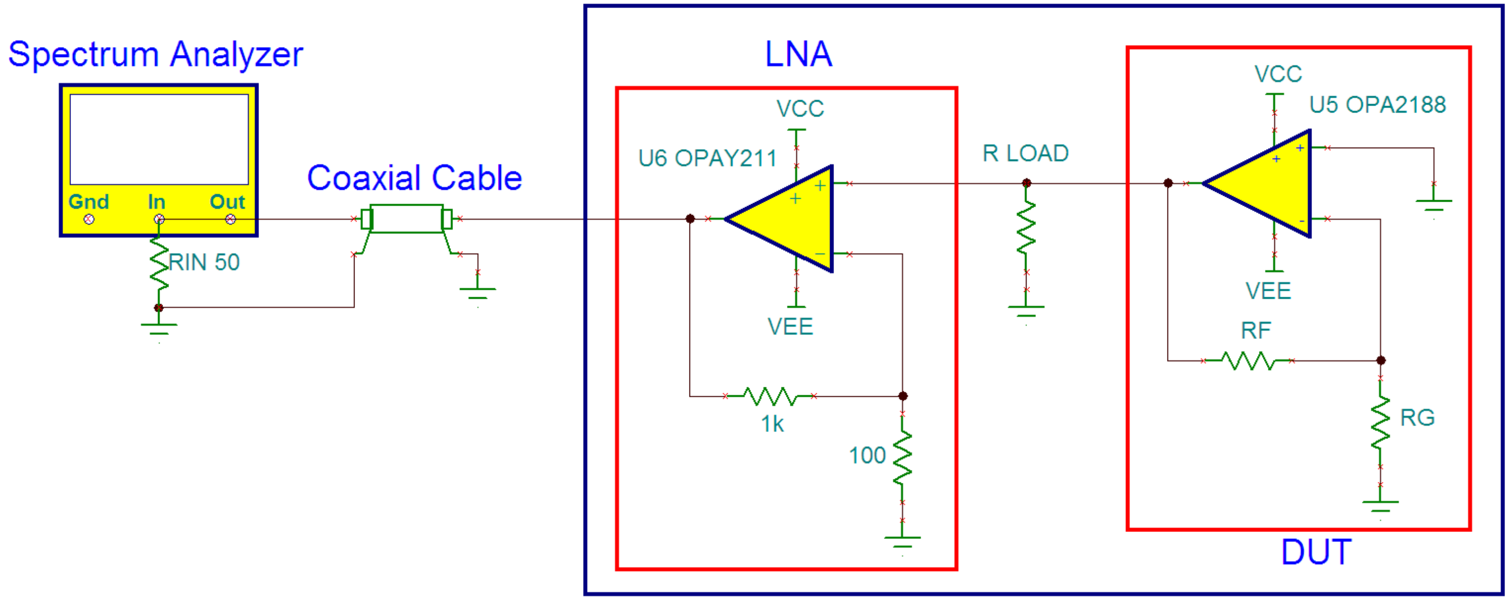
- The synchronous notch filter integrates the input waveform (on capacitor C) for one clock period
  - Switch Phase 1 closed
  - Switch Phase 2 open
- The integrated value is then passed to the output
  - Switch Phase 1 open
  - Switch Phase 2 closed
- This produces the transfer function shown at right




**By synchronizing the switches to the chopping frequency, TI choppers achieve a 500x reduction in noise**

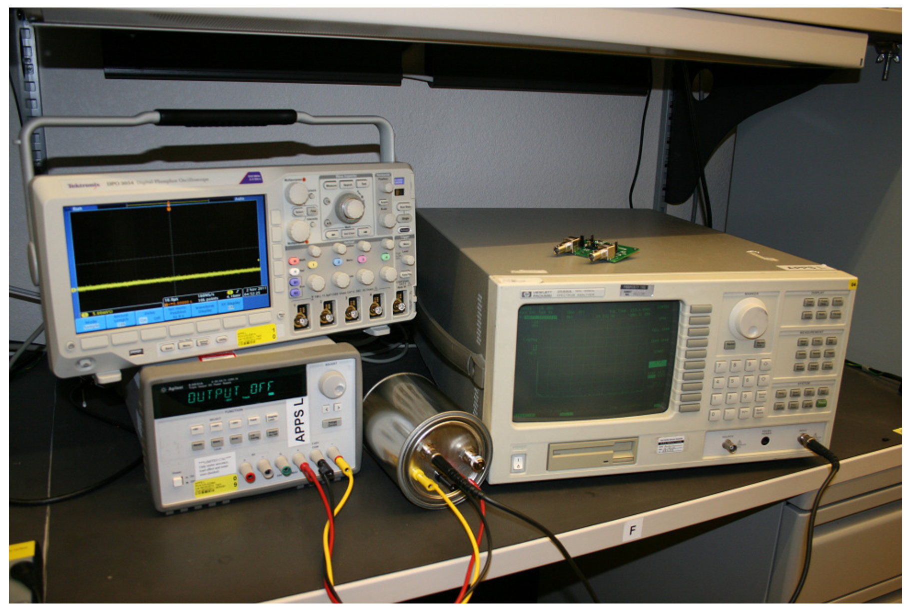


# Investigating Chopper Voltage Noise




- Output noise was amplified and viewed in the frequency domain
  - Low Noise Amplifier (LNA) was an OPA211 with a gain of 11
  - Agilent 35670A (.1 to 100kHz)
  - HP3588 (100kHz to 150MHz)
  - Shielded enclosure and cables
- Noise floor is measured first and subtracted from the final results

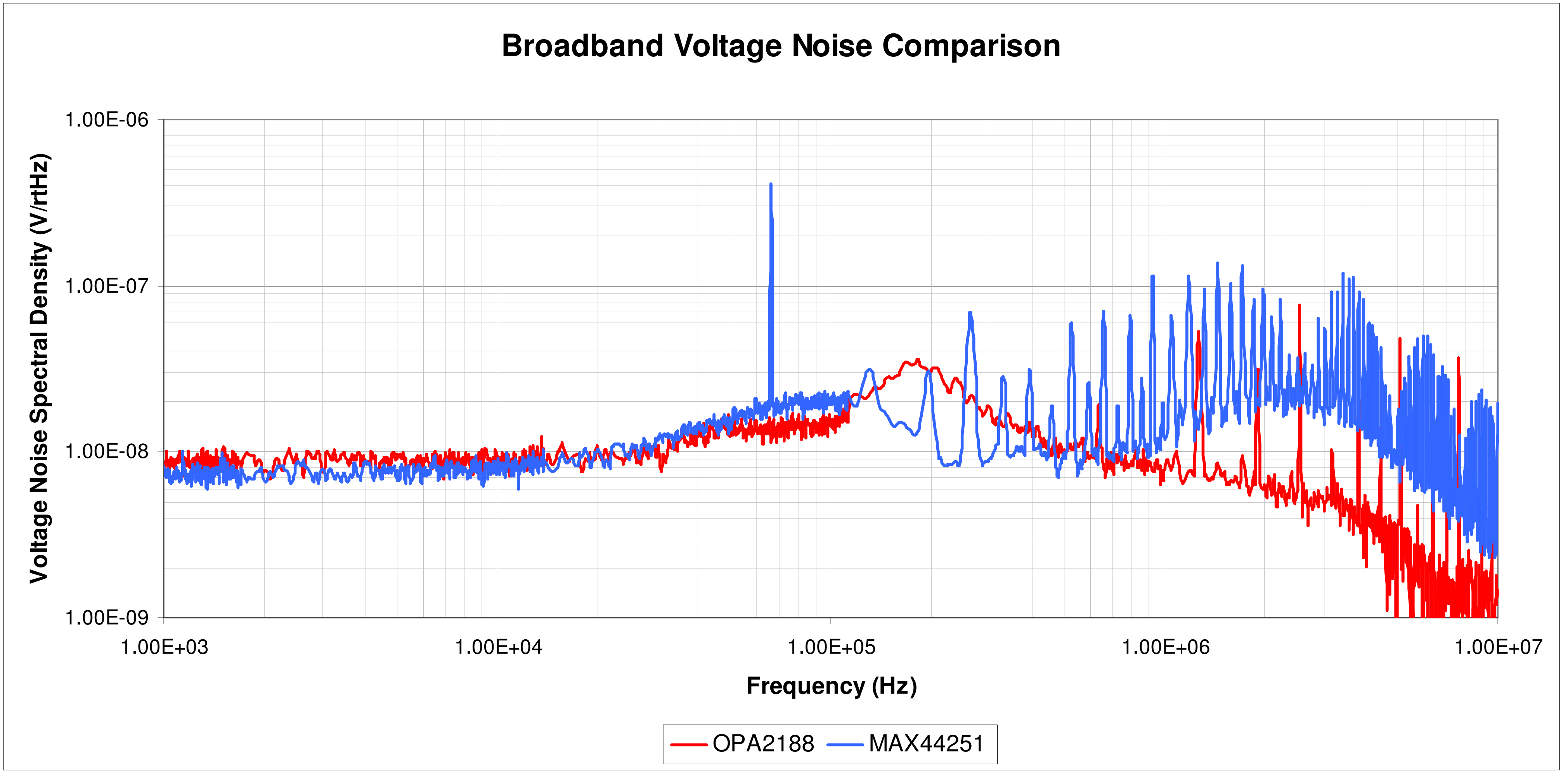
Shielded Enclosure



# Synchronous Notch Filter Effectiveness

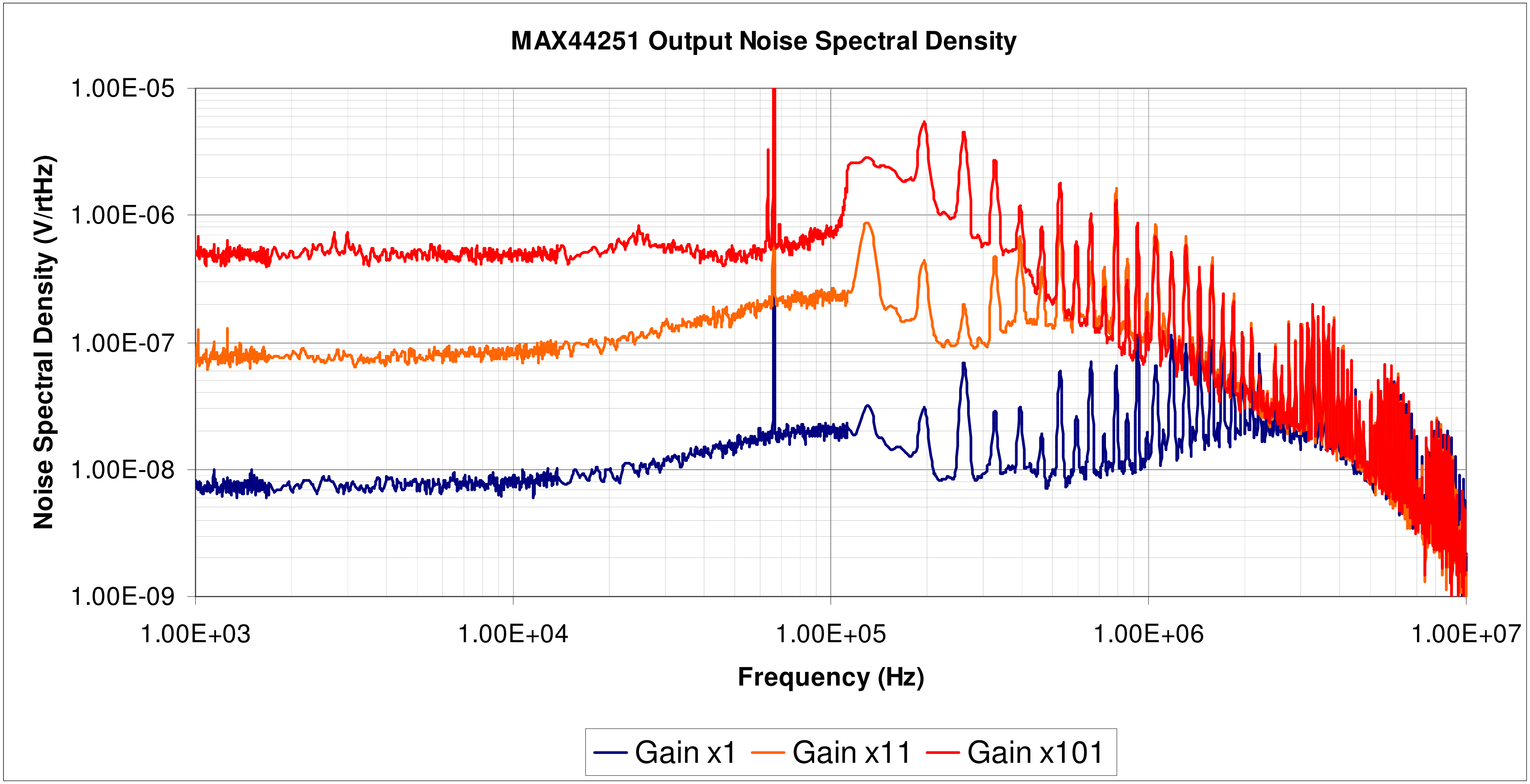
- OPA2188 Broadband Noise Spectral Density: 8.8 nV/rtHz
- MAX44251 Broadband Noise Spectral Density: 5.9 nV/rtHz

The MAXIM part is lower noise right?....Not Exactly



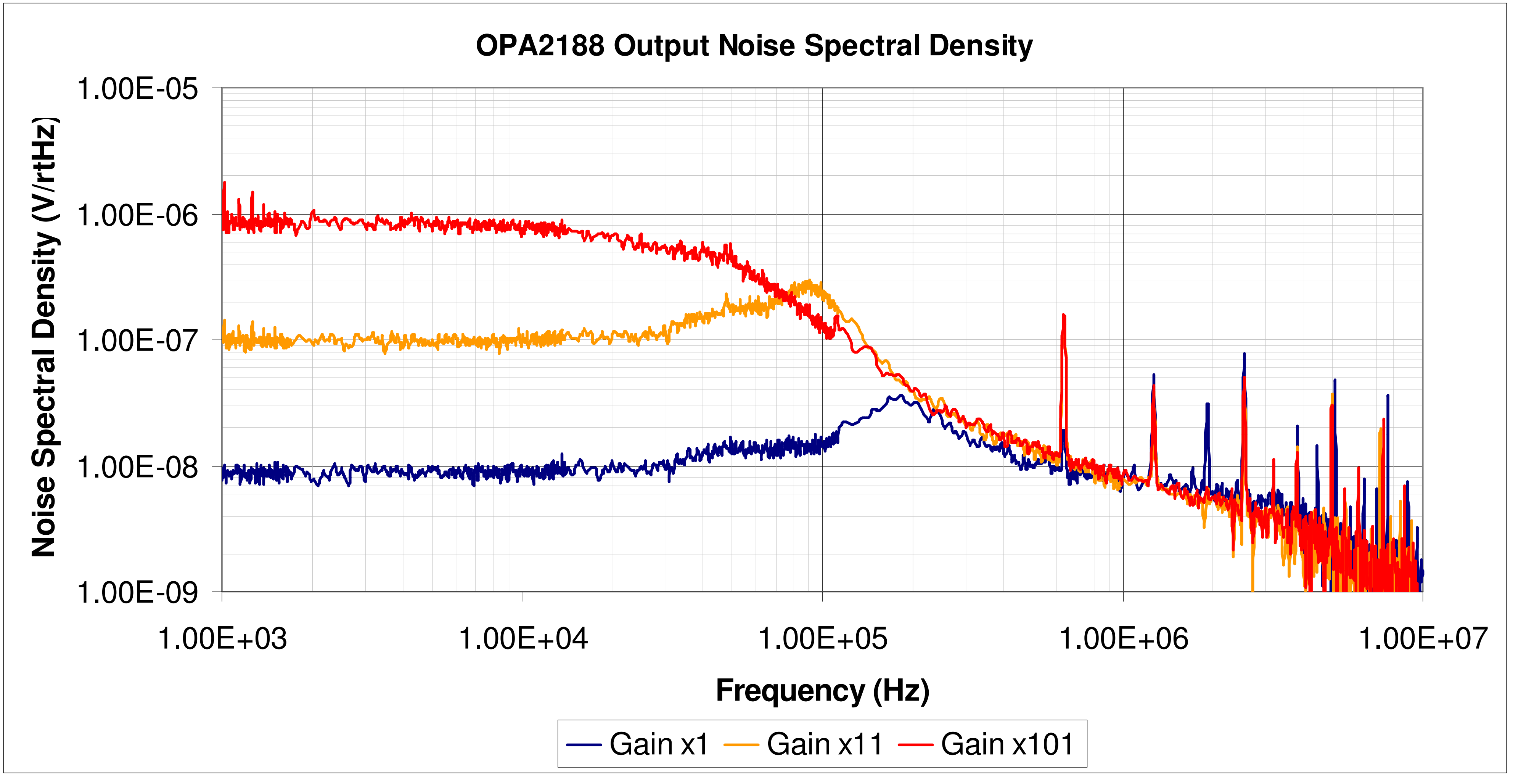
# Gain Effects on Total Noise: Chopping In-Band

- MAX44251: GBW 10MHz, Chopping frequency 65kHz
  - Broadband Noise Spectral Density: 5.9 nV/rtHz
  - Chopper noise scales with gain!→ Input referred



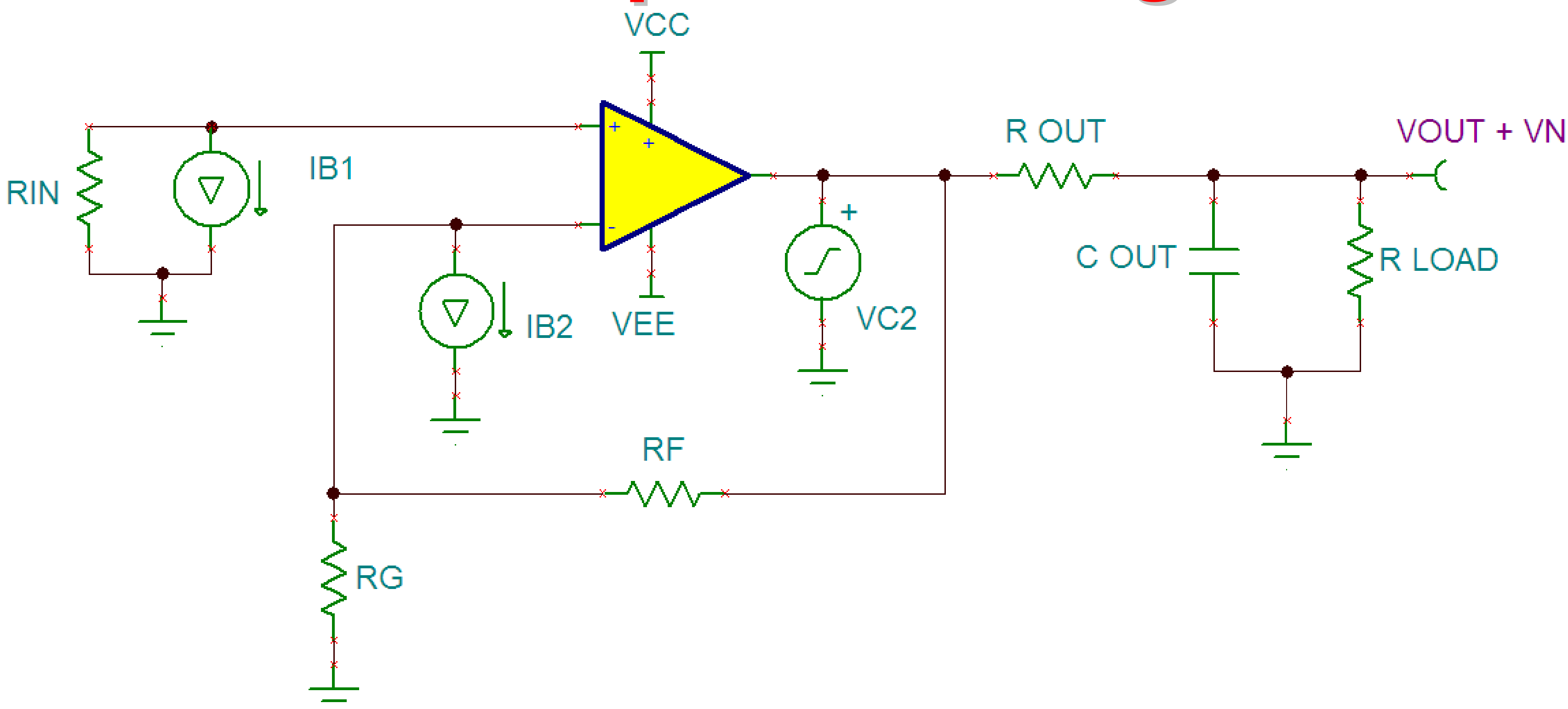
# Gain Effects on Total Noise: Chopping Out-of-Band

- OPA2188: GBW 3MHz, Chopping Frequency >650kHz
  - Broadband Noise Spectral Density: 8.8 nV/rtHz, synchronous notch filtering
  - Chopper noise scaling with gain is minimal → Output referred



# Application Tips

# Output Filtering



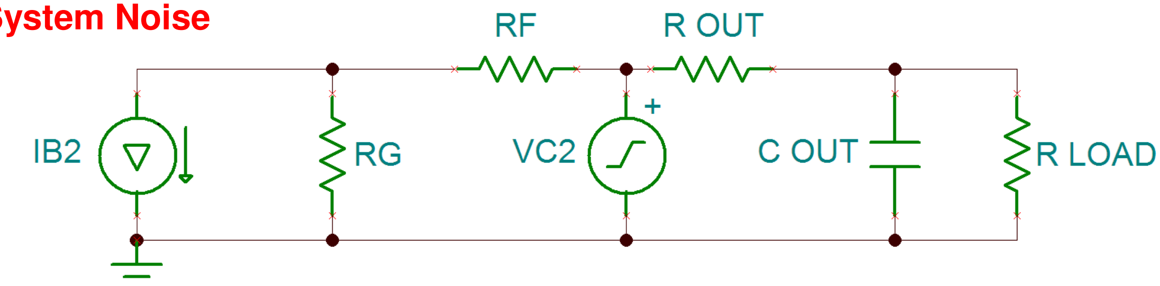

Adding an RC output filter can mitigate noise seen by high impedance loads

- $C_{OUT}$ chosen to have an impedance much less than $R_{LOAD}$ at the chopping frequency
- $R_{OUT}$ chosen to maintain opamp stability with the chosen $C_{OUT}$

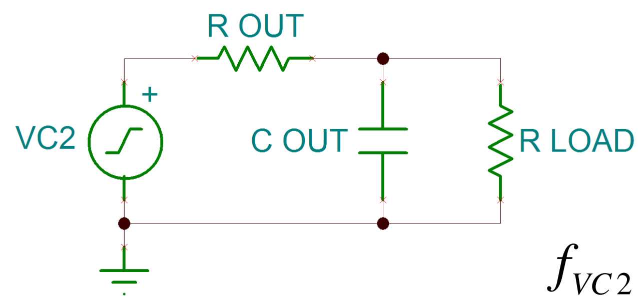
# Output Filtering

- The contributions of the individual noise sources can be visualized with the circuit at right
- The corner frequency of the filter as seen by the voltage noise is directly determined by Rout and Cout
- The corner frequency for the transient current noise is actually much lower
  - The filter now includes the feedback resistance RF
  - Filter corner frequency can be chosen to remove current noise without affecting desired signal
  - RG also attenuates the noise developed across the load

**System Noise**

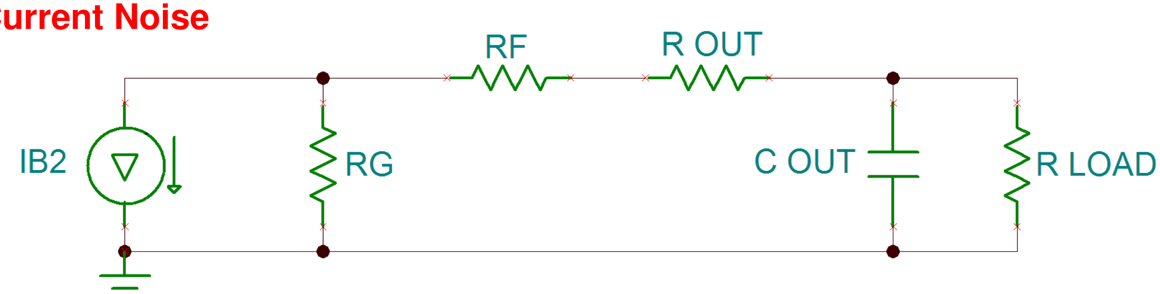



**Voltage Noise**




$$f_{VC2} = \frac{1}{2\pi * R_{OUT} * C_{OUT}}$$

**Current Noise**




$$f_{IB2} = \frac{1}{2\pi * (R_{OUT} + R_F) * C_{OUT}}$$

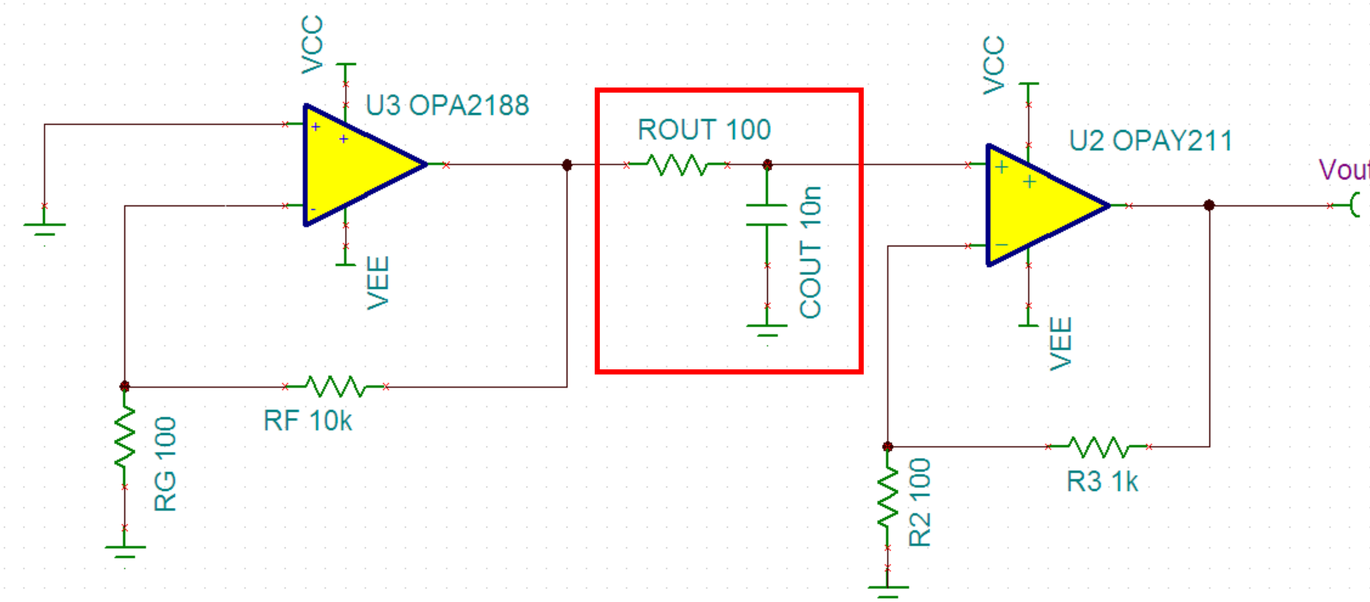
# Output Filtering Example

Consider the addition of an output RC filter to an OPA2188:

$R_F$: 10kOhms, $R_G$: 100 Ohms

$R_{OUT}$: 100 Ohms, $C_{OUT}$: 10nF

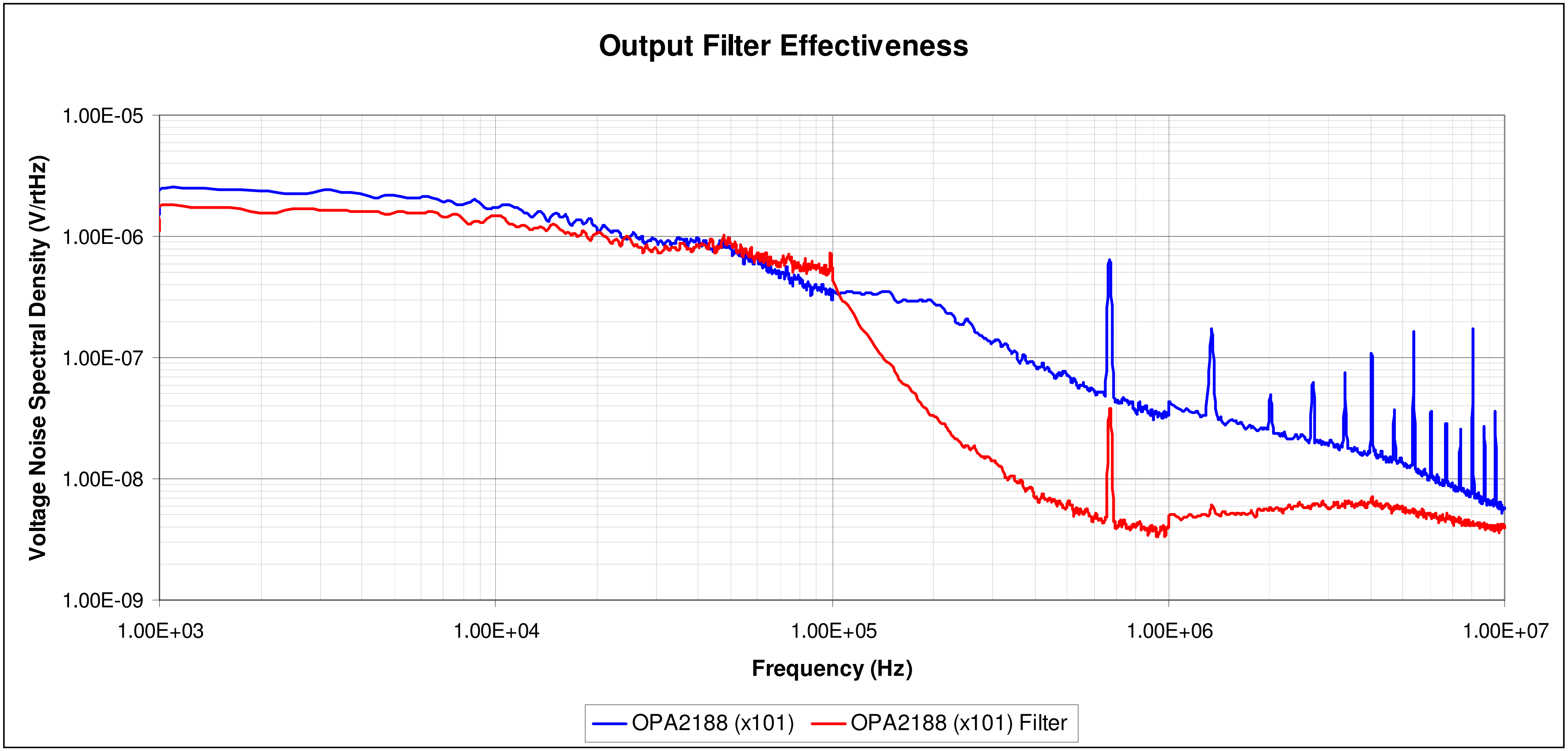
The measurement circuit and calculation of the two corner frequencies created by this filter are shown below:




$$f_{VC2} = \frac{1}{2\pi * R_{OUT} * C_{OUT}} = \frac{1}{2\pi * 100\Omega * 10nF} = 159kHz$$

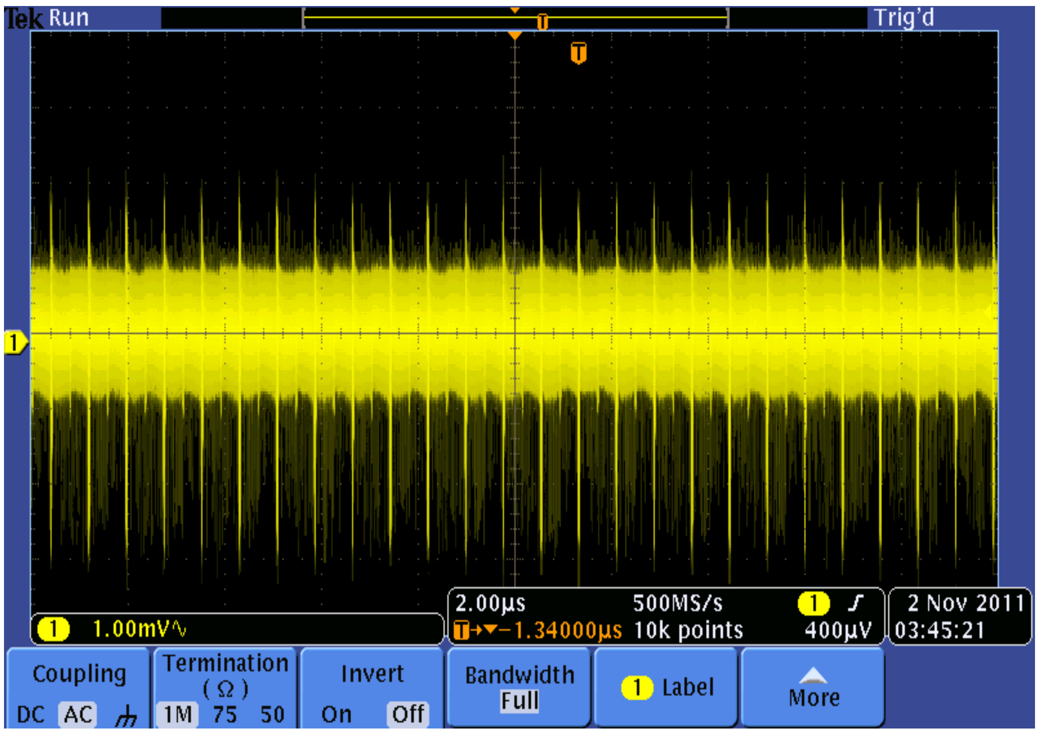
$$f_{IB2} = \frac{1}{2\pi * (R_{OUT} + R_F) * C_{OUT}} = \frac{1}{2\pi * (100\Omega + 10k\Omega) * 10nF} = 1.576kHz$$

# Output Filtering



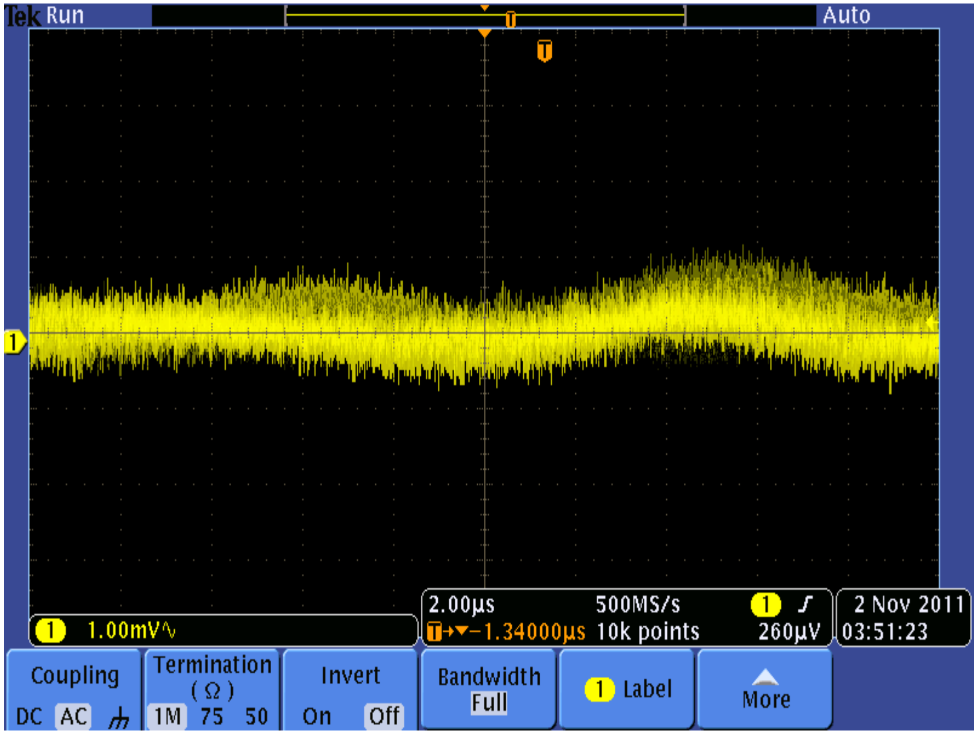

- Harmonics due to input current spikes are completely eliminated
- Noise at chopping frequency travels through the opamp (not around the feedback network)

# Output Filtering




OPA2188 Without Filtering

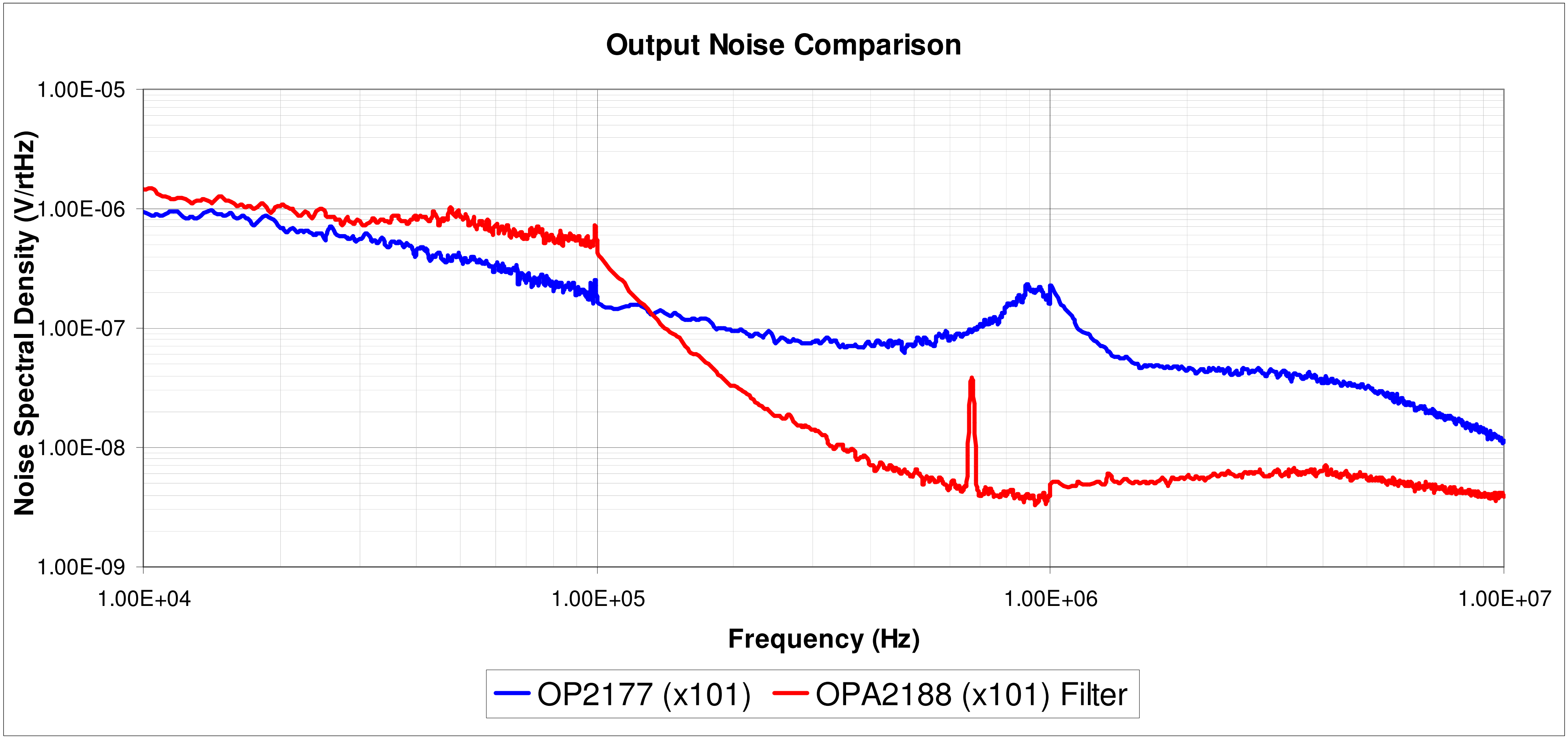
- Gain: 101, RF:10k, RG:100 Ohm
- Oscilloscope 1MOhm input impedance is the load
- Input current spikes are visible above other noise sources




OPA2188 With Filtering

- Gain: 101 RF: 10k, RG: 100 Ohm
- Oscilloscope 1MOhm input impedance is the load

# Comparison to Non-Chopper Amplifiers




The filtered output spectrum of the OPA2188 was compared to a traditional precision bipolar part

- Removal of the chopping noise makes the high frequency noise spectrum comparable.

# Minimizing Chopper Noise Effects

- Input current spikes are not amplified by the part
  - Spikes on the inverting input will be coupled to the load by the feedback network
- Minimize feedback resistance values
  - Reduces the voltage produced by current spikes
  - Standard design practice for low-noise, low-drift circuits
- Load impedance directly contributes to the magnitude of voltage produced by the spike
- An RC filter is an extremely effective way to reduce output noise
  - Most practical with high-impedance loads
  - Corner frequency can be placed outside of the signal bandwidth
  - Noise through the feedback network experiences a much greater attenuation

# Thank You!