Digital-to-Analog Converter (DAC) Output Response

TIPL 4705

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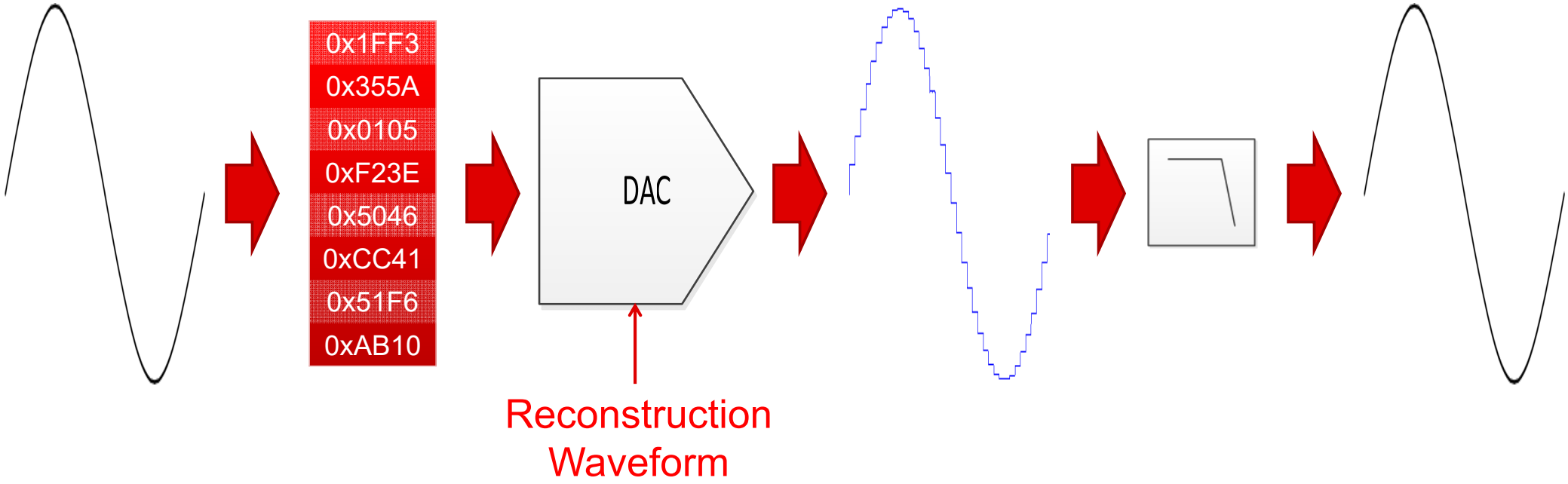
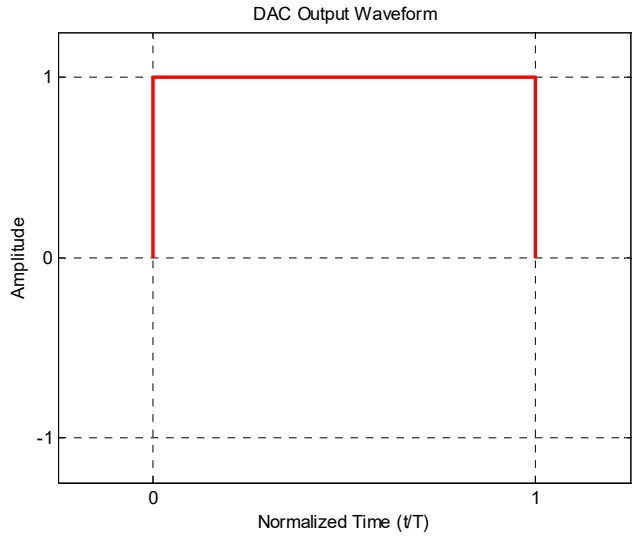
What is a Digital-to-Analog Converter (DAC)?

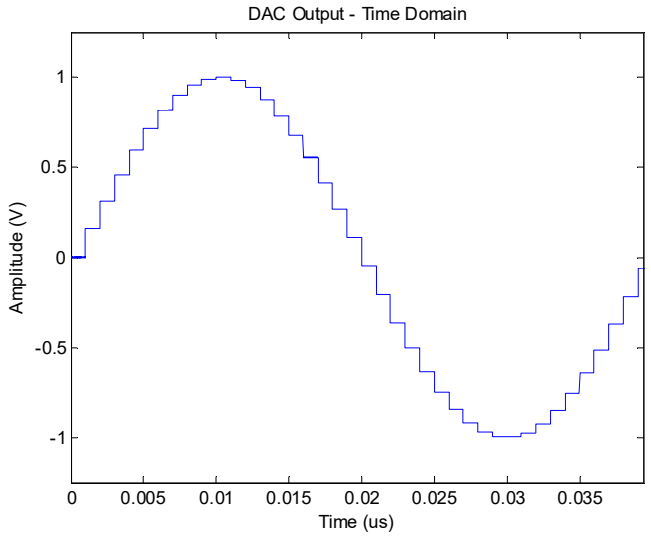


Reconstruction Waveform – Time Domain

- A reconstruction waveform determines the output response of a DAC, in both time domain and frequency domain
- At each sampling instance the DAC outputs the waveform weighted by the digital sample

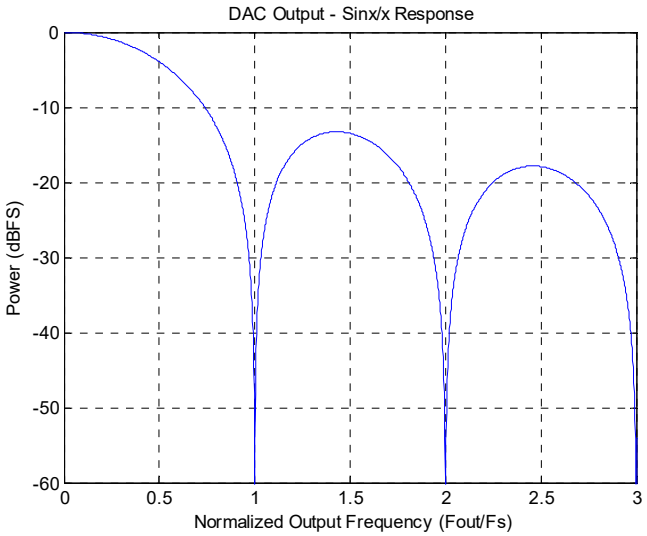


Weighted by digital samples

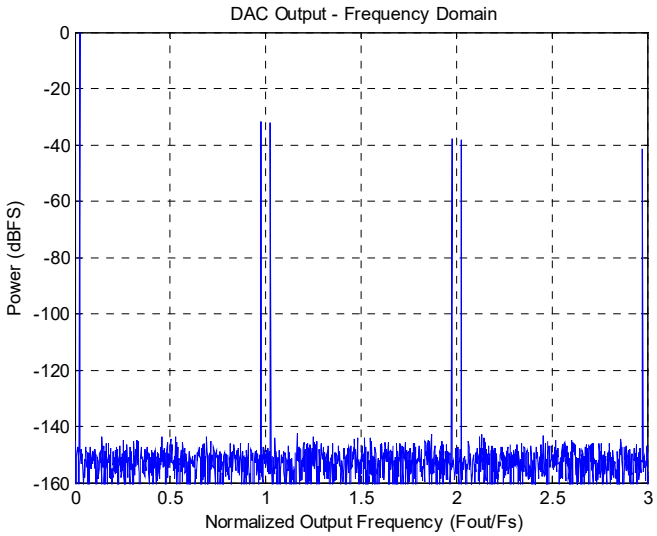


Reconstruction Waveform – Frequency Domain

- The shape of the reconstruction waveform results in a certain frequency response
- The frequency response determines the output power of the desired signal as well as the power of some undesired signals



Weighted by digital samples



What is a Nyquist Zone?

- A Nyquist zone corresponds to a band of frequencies Fs/2 wide, where F_S is the DAC's sampling rate
- Each Nyquist zone is $F_S/2$ wide, starting at DC:
  - The 1st Nyquist zone extends from DC to $F_S/2$
  - The 2nd Nyquist zone extends from $F_S/2$ to F_S
  - And so on…
- Note that even Nyquist zones have a mirrored spectrum

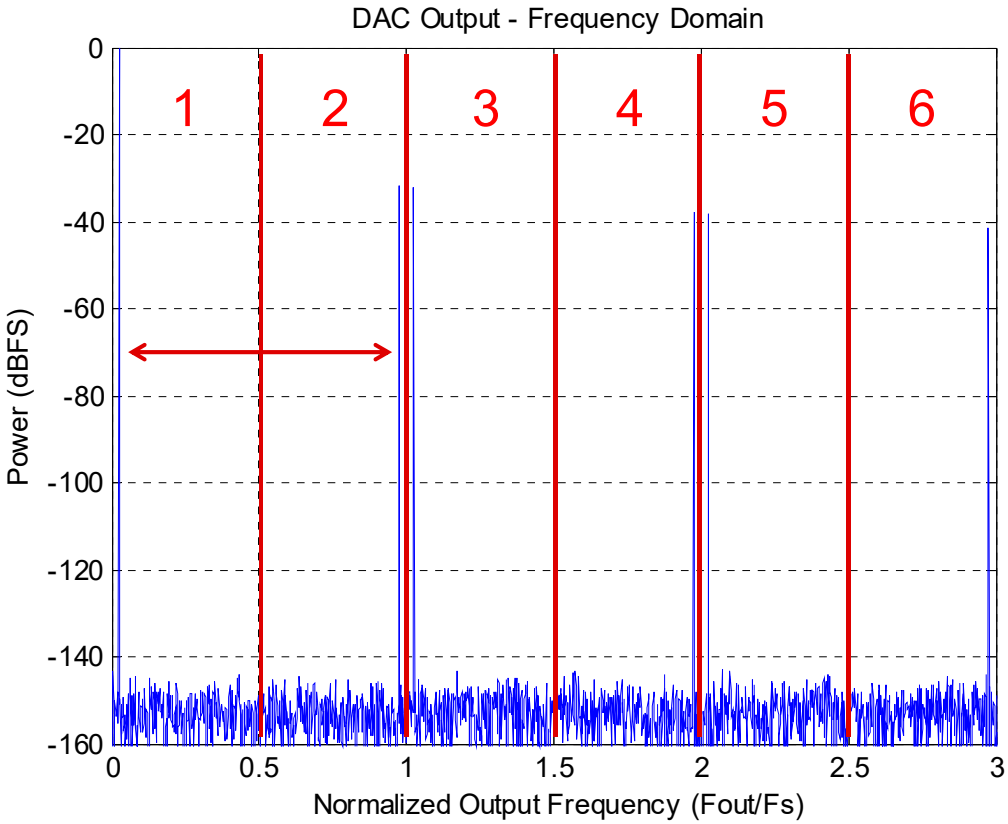
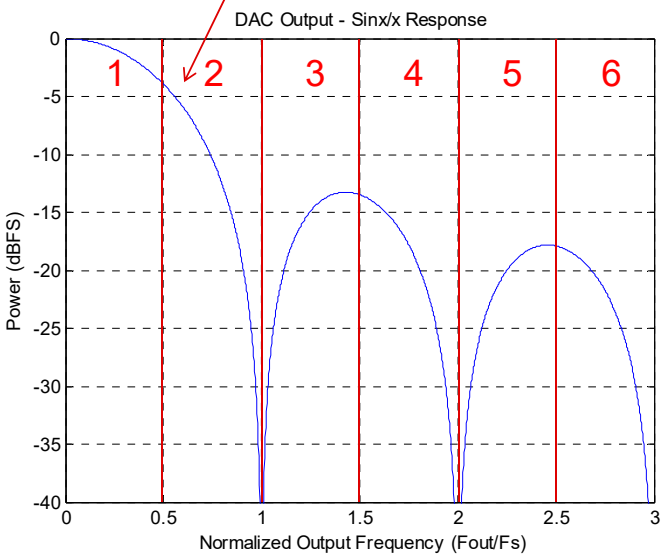


Illustration of DAC Output Response

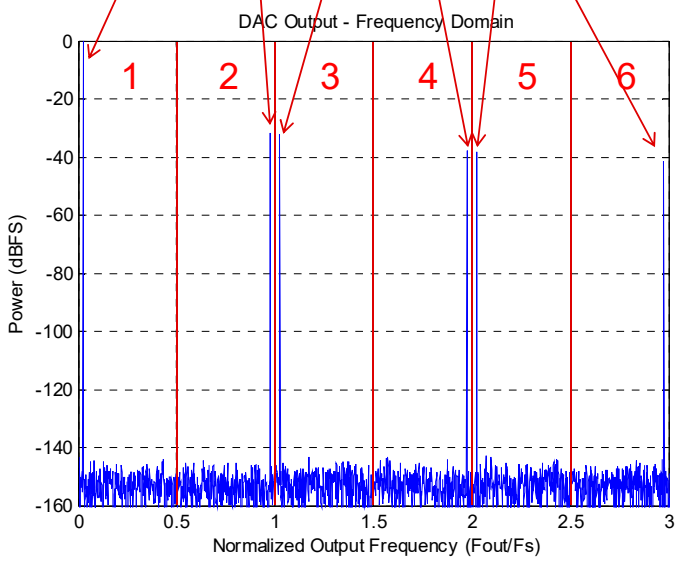
Loss of output power at higher frequencies due to sinc response



DAC Sinx/x Response for Zero-Order Hold Reconstruction Waveform

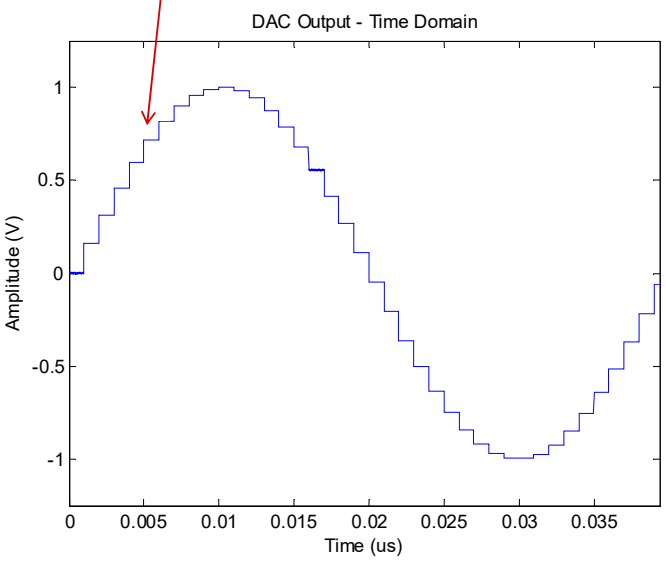
Images in other Nyquist zones must be filtered out

Desired signal



DAC Frequency Domain for Sine Wave Output and ZOH Reconstruction Waveform

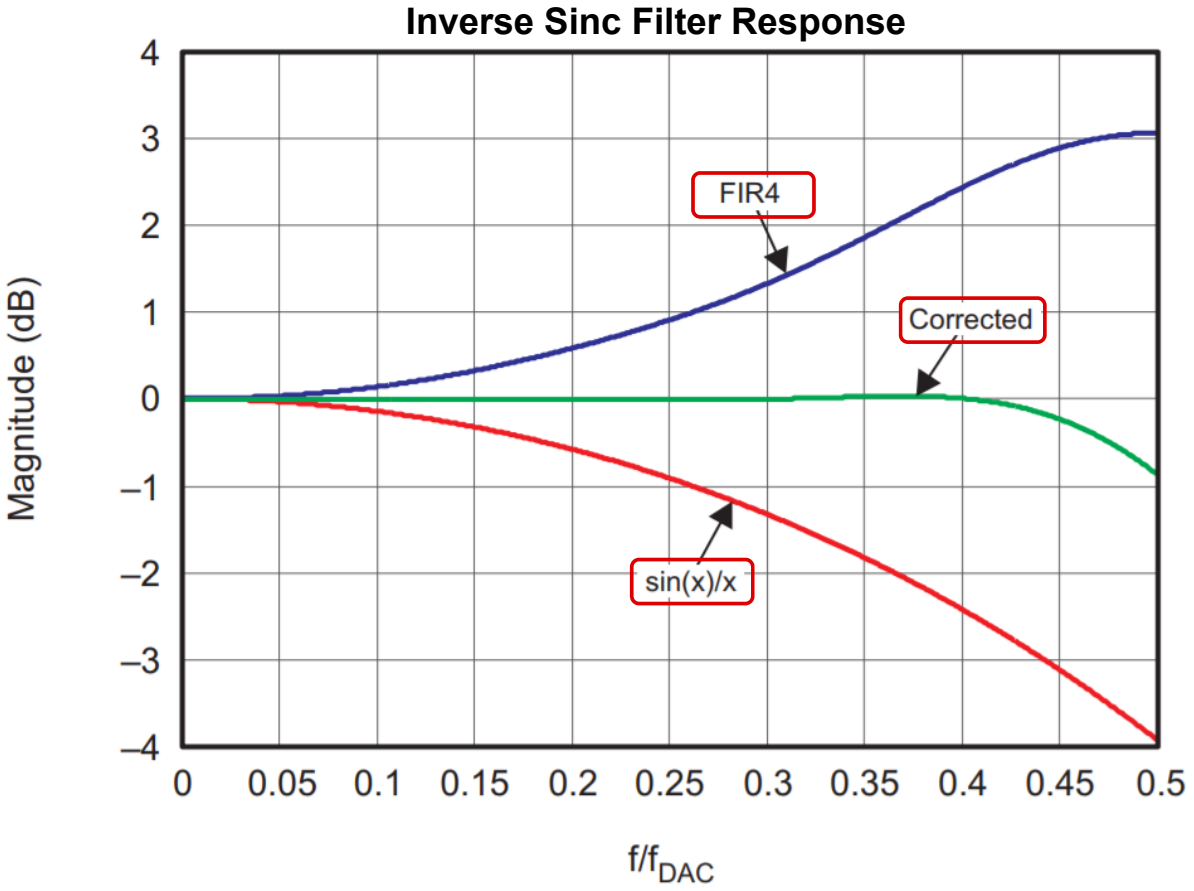
Images result in stair-case response in reconstructed waveform



DAC Time Domain for Sine Wave Output and ZOH Reconstruction Waveform

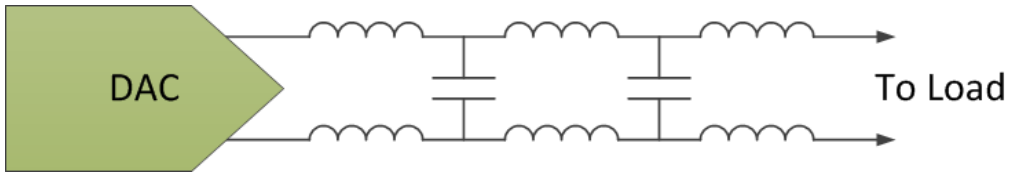
Inverse Sinc Filter

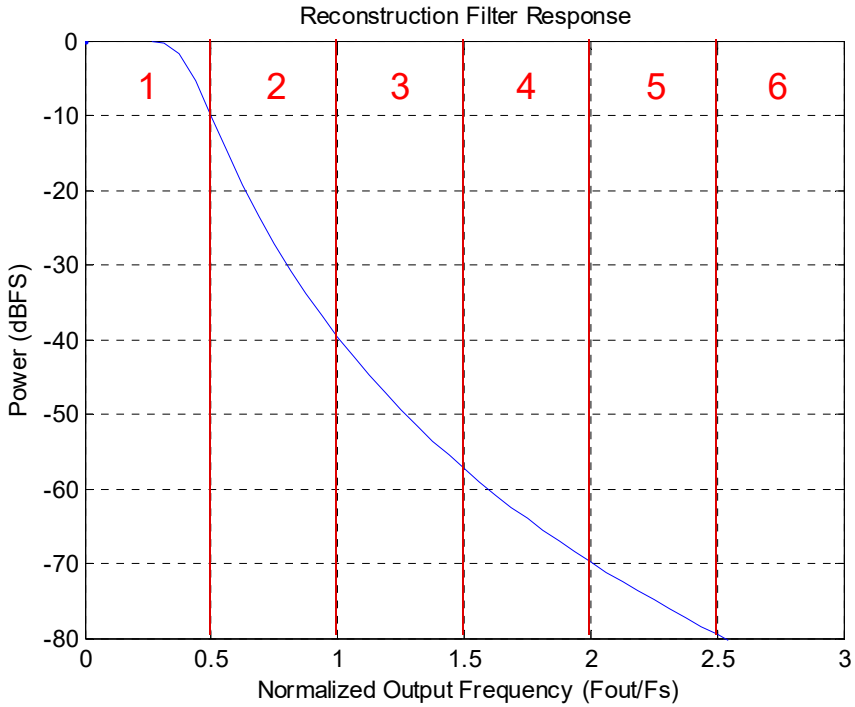
- A simple method used to recover the output power loss due to the sinc response is to use a digital filter to apply gain at higher frequencies
- This example filter flattens the output response through ~80% of the Nyquist zone
- Care must be taken to ensure that the applied gain does not cause saturation of the digital path for full scale signals



Reconstruction Filter

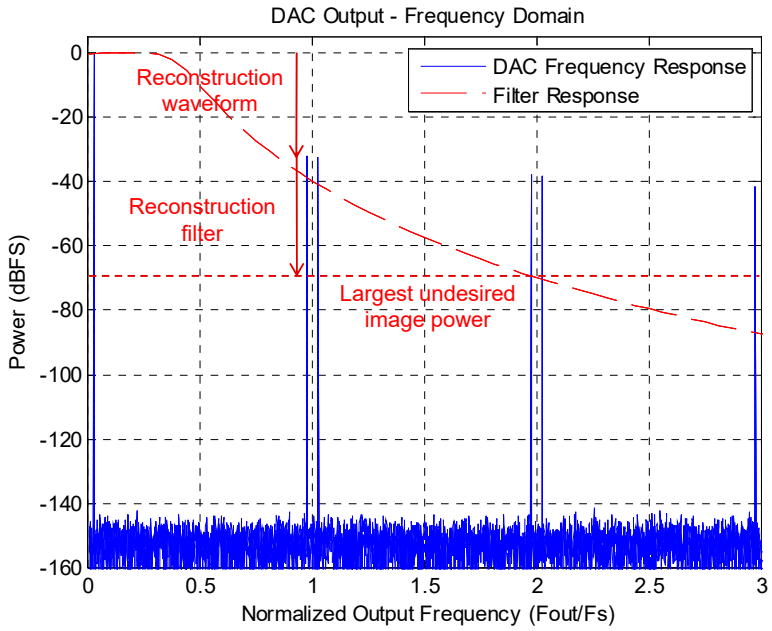
- An analog filter is required at the output of the DAC to select the desired image signal and attenuate the undesired images
- This analog filter is called a "reconstruction filter"
- An example (ideal) 5th-order low-pass Butterworth filter is shown with a cutoff frequency at 80% of the 1st Nyquist zone

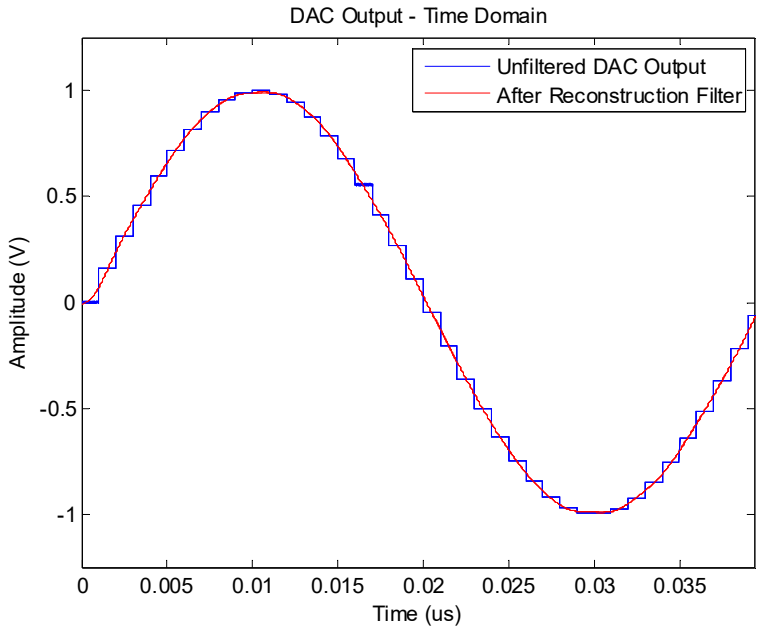




Reconstruction Filter Example

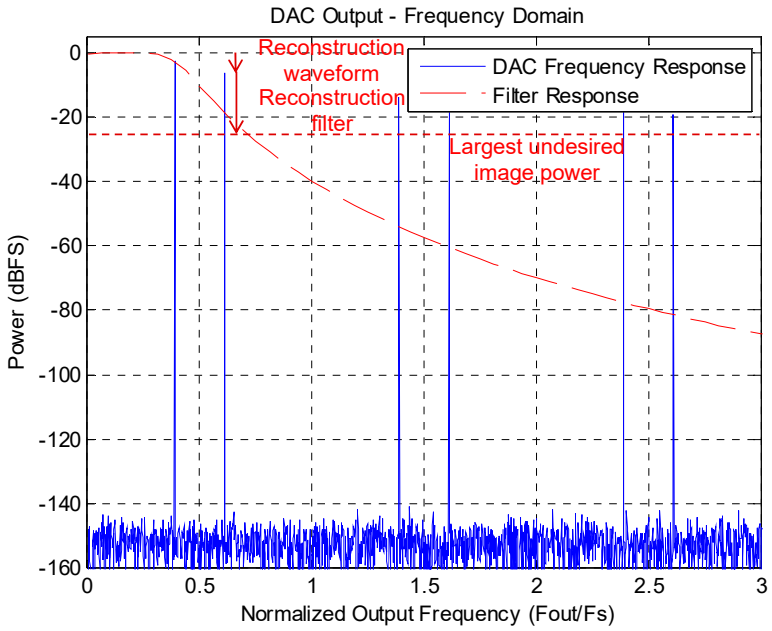
- F_S = 1 Gsps, F_{OUT} = 30 MHz
- Attenuation of 2nd Nyquist zone image = ~40 dB
- Stair-case DAC output becomes a smooth sine wave after image removal

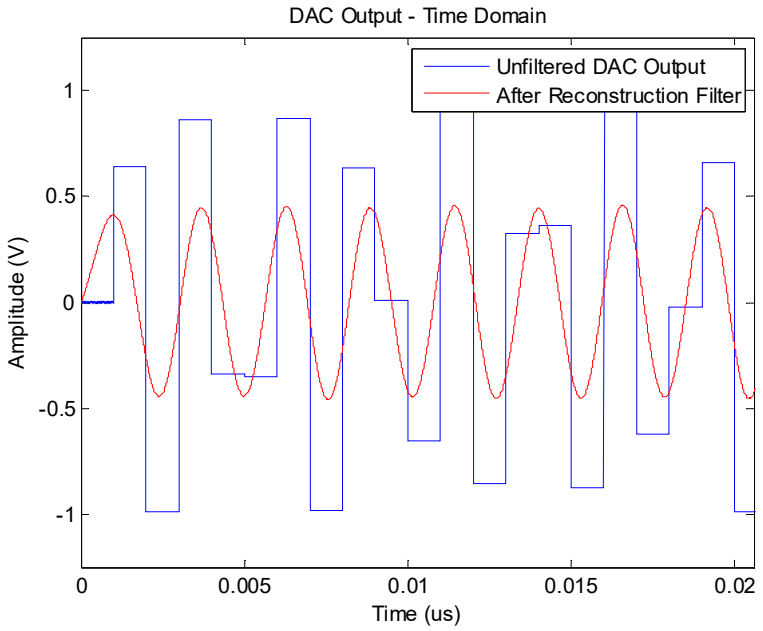




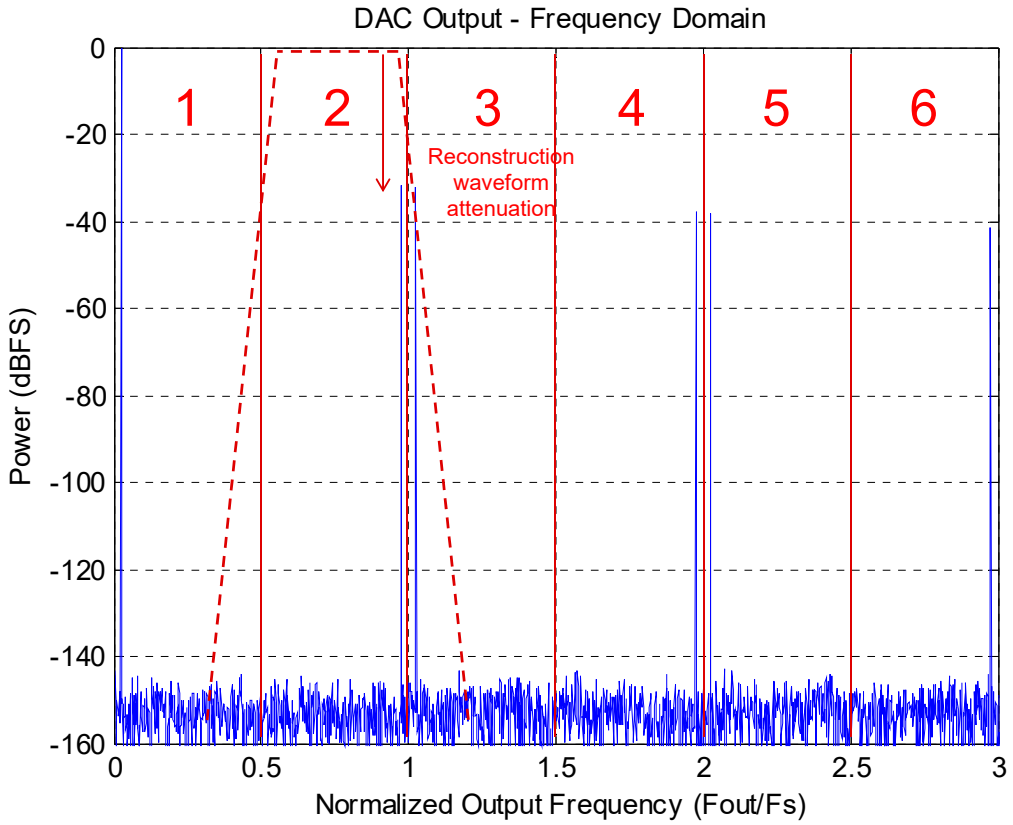
Reconstruction Filter Example

- F_S = 1 Gsps, F_{OUT} = 400 MHz
- Attenuation of 2nd Nyquist zone image = ~18 dB
- May want to increase cutoff frequency and increase filter order





Can we use the image in a different Nyquist zone?

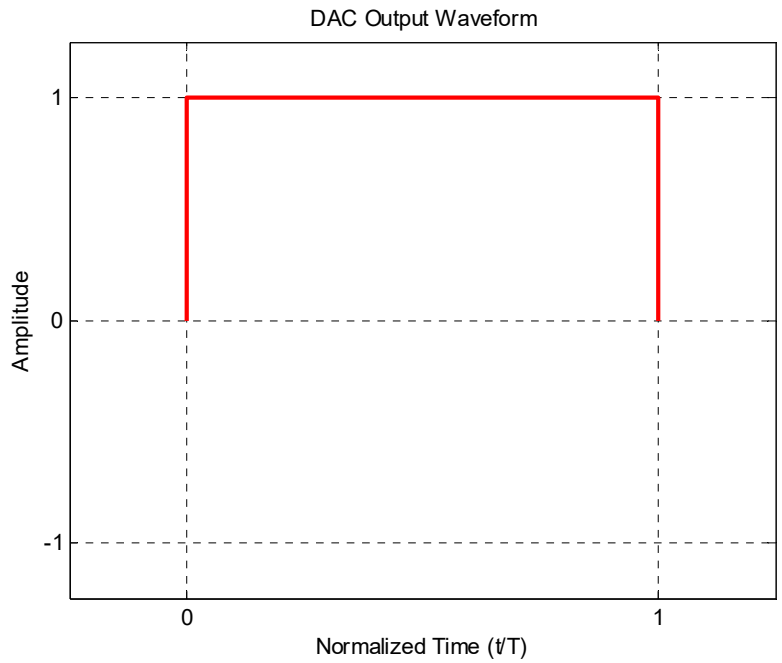


Multi-Nyquist Modes

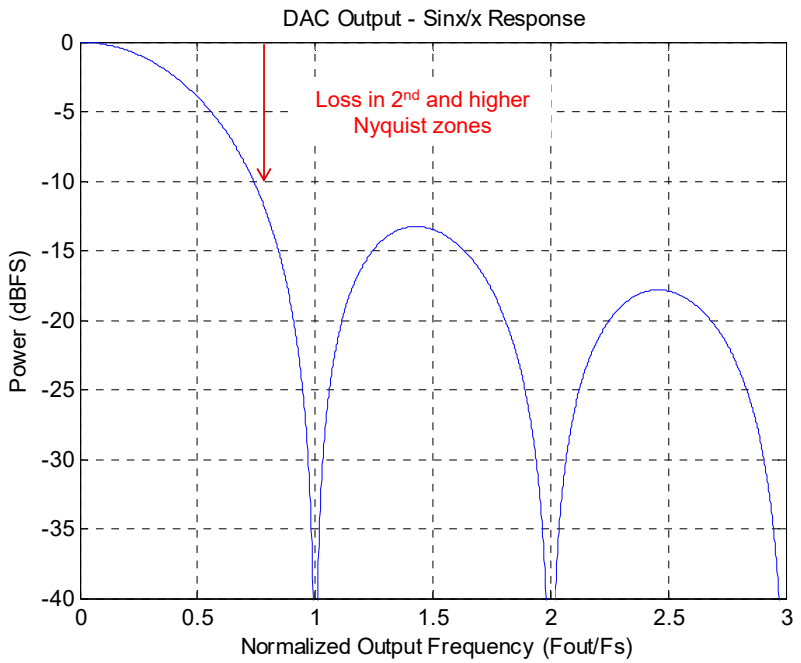
- The common ZOH reconstruction waveform results in a fairly flat response in the 1st Nyquist zone, but suffers from high loss in higher Nyquist zones
- If an alternate Nyquist zone image is desired, then a different reconstruction waveform should be used
- Common reconstruction waveforms:
  - Zero-Order Hold (ZOH) or Non-Return-to-Zero (NRZ) – 1st Nyquist only
  - Return-to-Zero (RTZ) – 1st and 2nd Nyquist
  - Return-to-Complement (RTC), also called Mixed Mode or RF Mode – 2nd and 3rd
- Adjustable reset pulses can also be added to these waveforms to further enhance high frequency output power and flatness
- The reconstruction waveform is a tradeoff of output power and flatness

Zero-Order Hold (or Non-return to Zero, NRZ)

Reconstruction Waveform

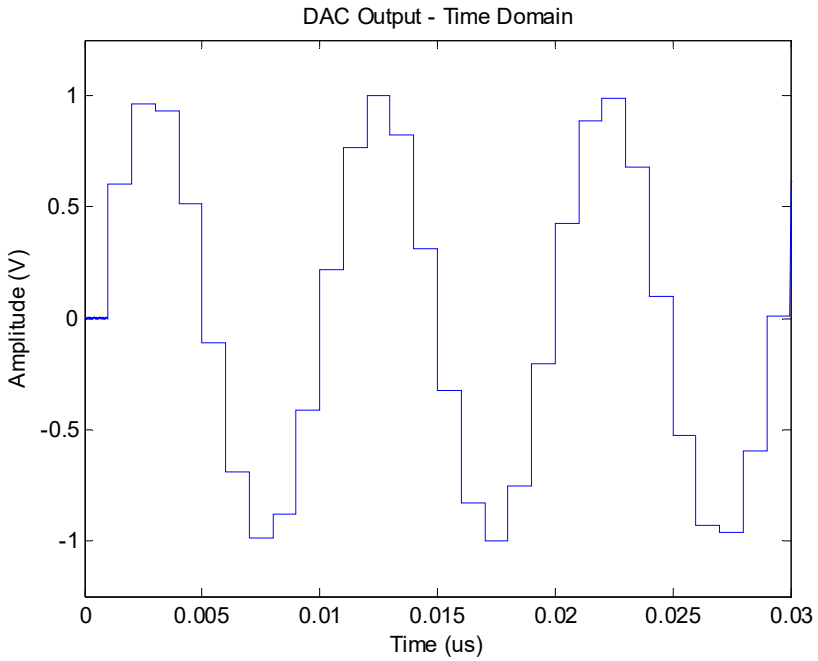


Frequency Response

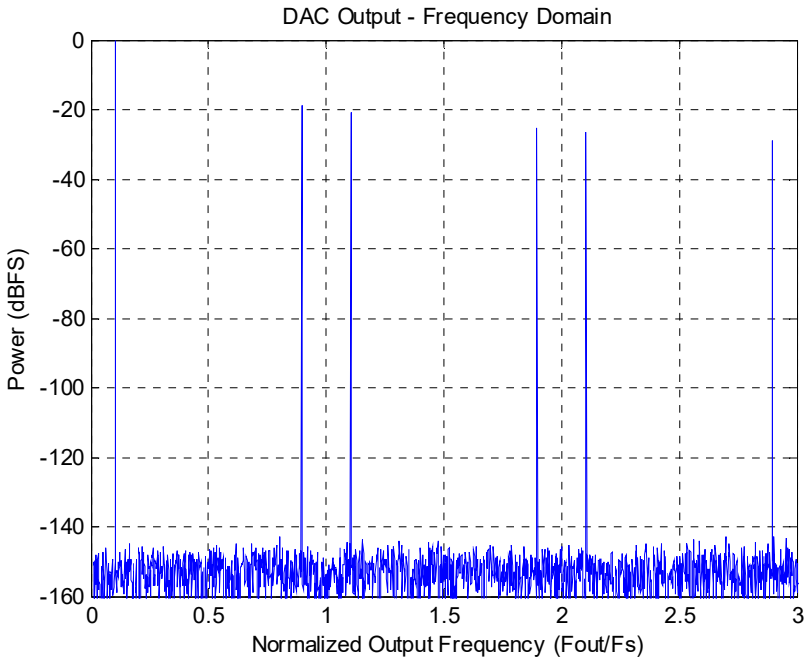


Zero-Order Hold (or Non-return to Zero, NRZ)

Time Domain Waveform

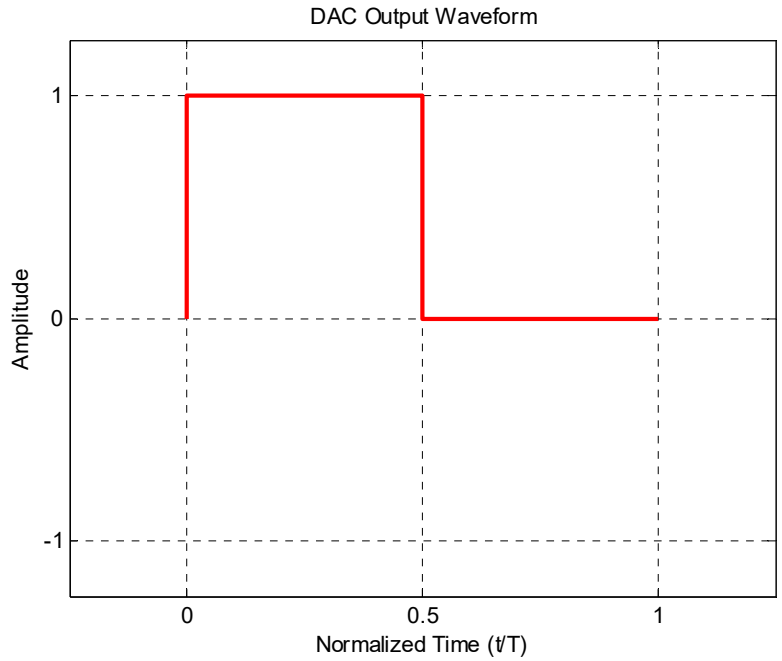


Frequency Domain

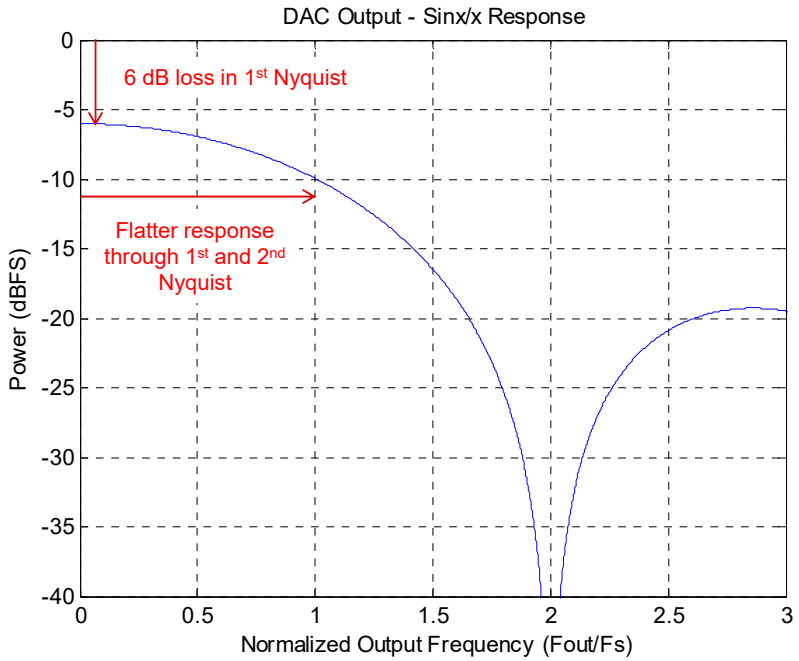


Return-to-Zero (RTZ)

Reconstruction Waveform

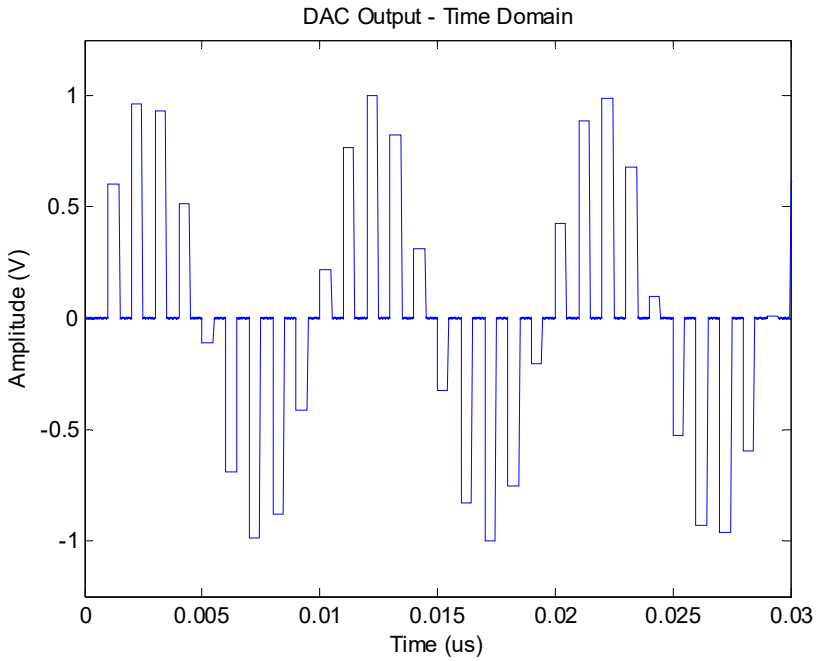


Frequency Response

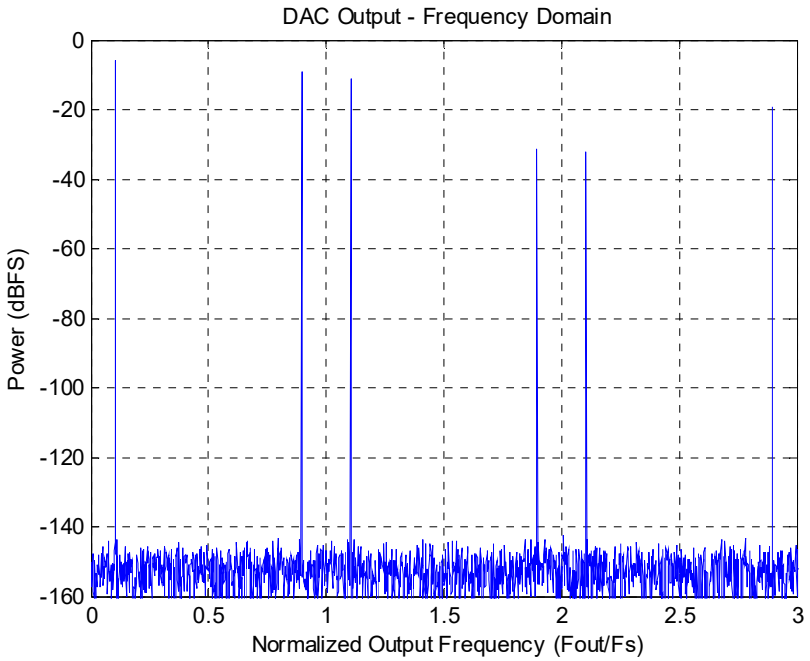


Return-to-Zero (RTZ)

Time Domain Waveform

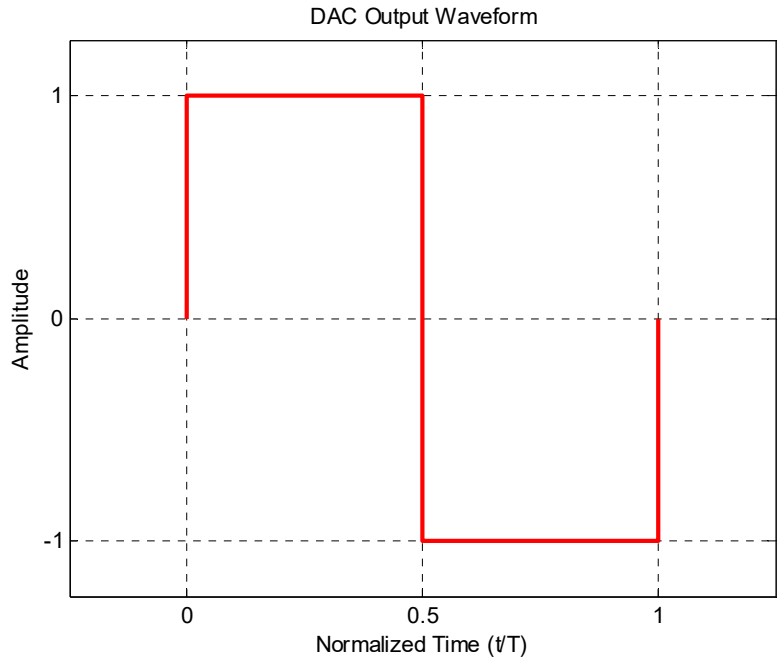


Frequency Domain

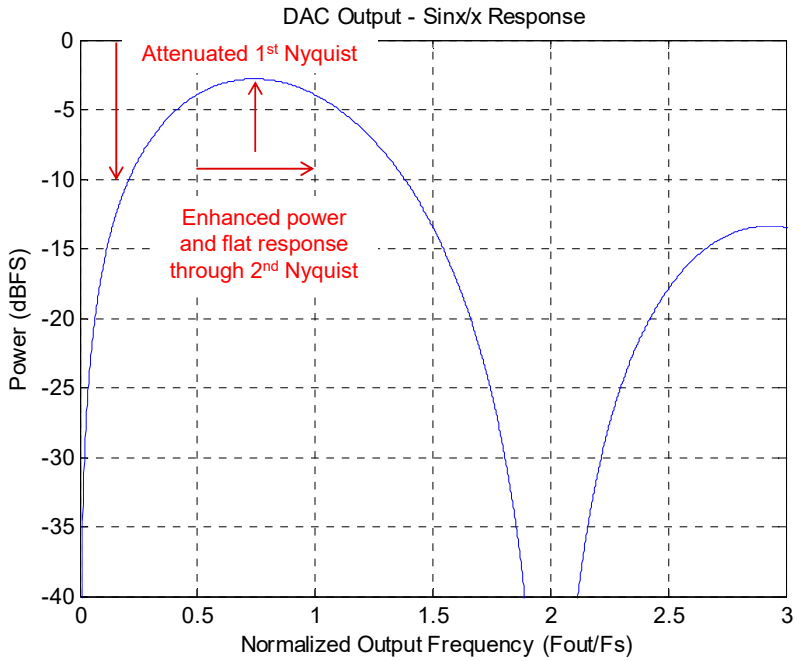


Return-to-Complement (RTC) or Mixed Mode

Time Domain

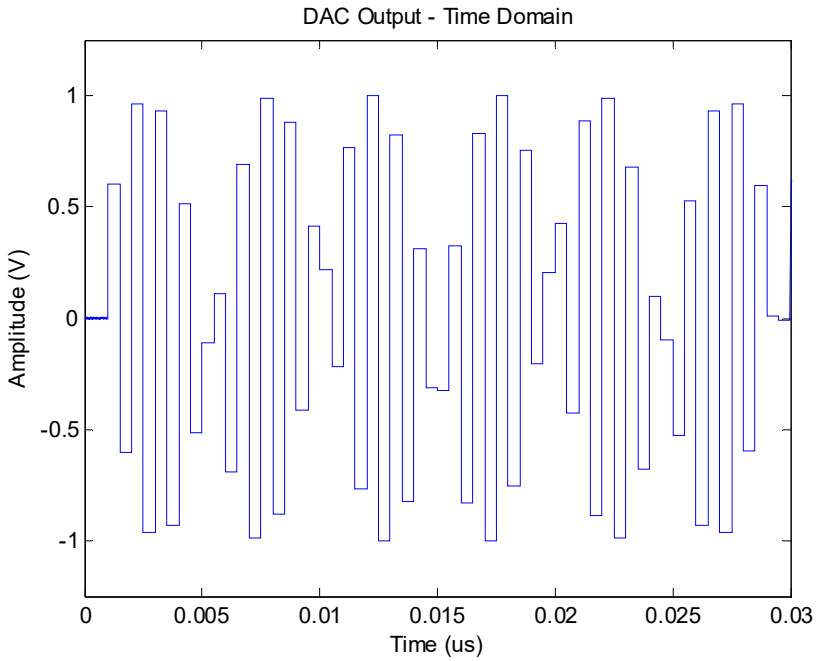


Frequency Domain

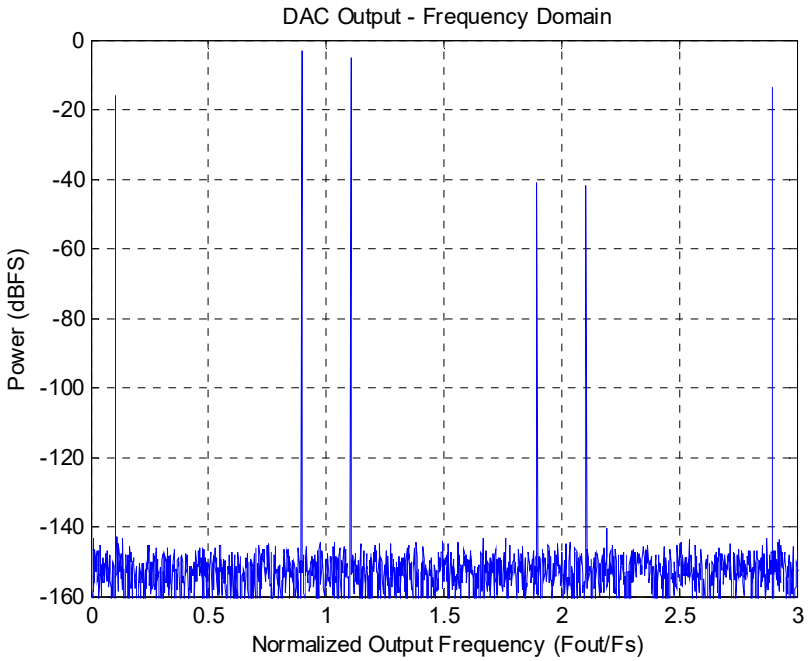


Return-to-Complement (RTC) or Mixed Mode

Time Domain Waveform

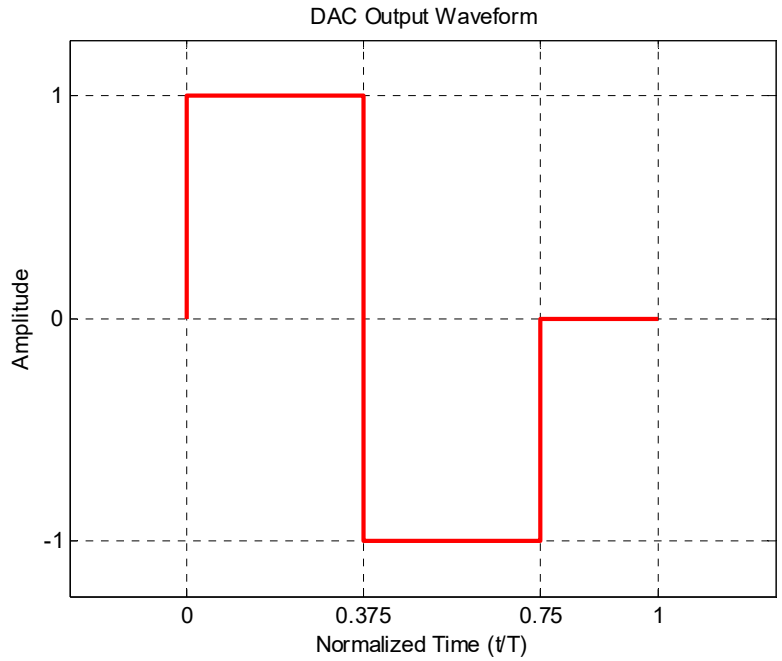


Frequency Domain

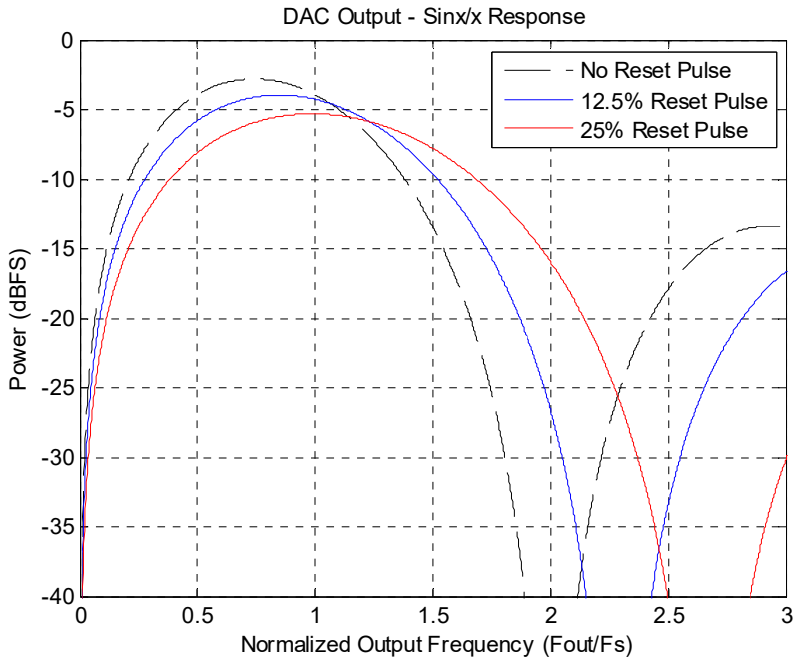


Return-to-Complement with Reset Pulse

Time Domain

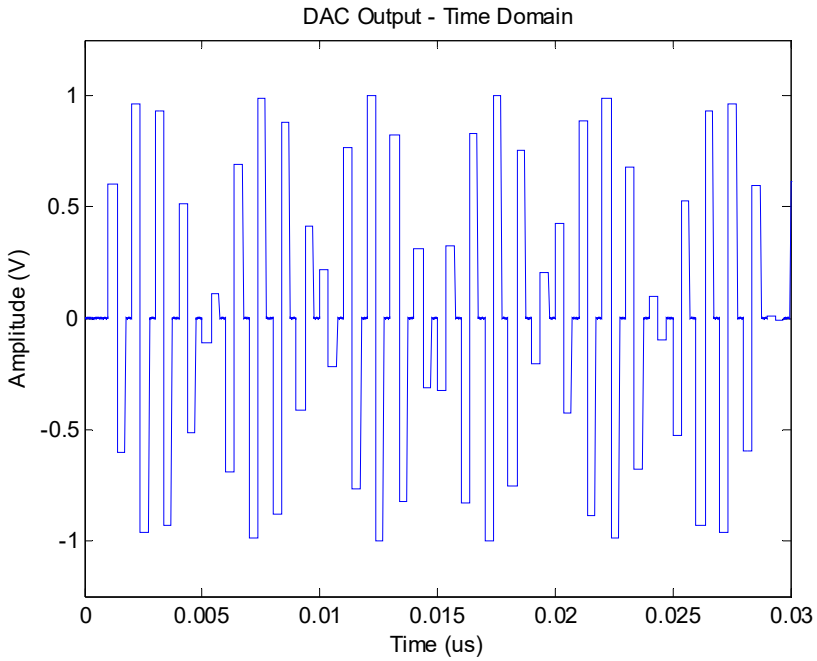


Frequency Domain

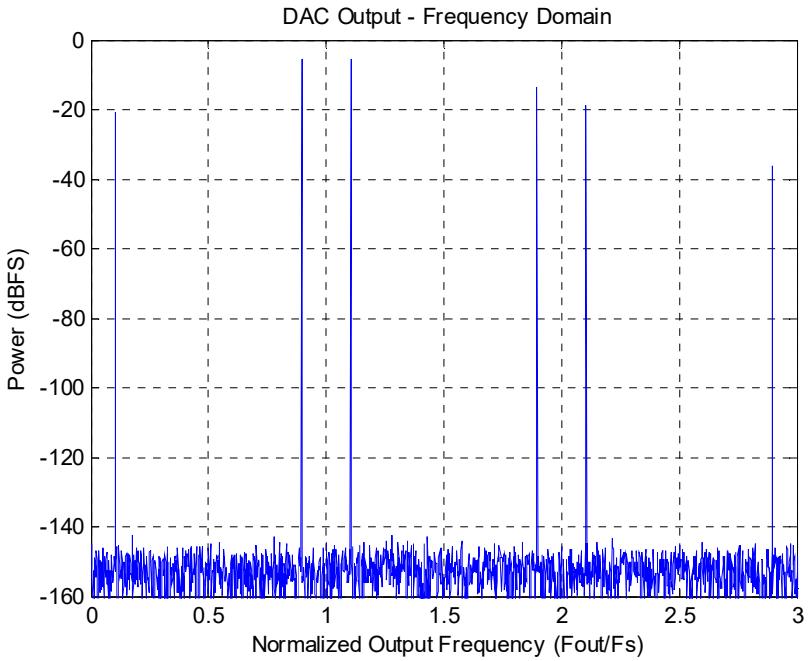


Return-to-Complement (Mixed Mode)

Time Domain Waveform



Frequency Domain



Effect of Limited Output Bandwidth

- The effect of the reconstruction waveform and reconstruction filters and their effect on output power of desired and undesired signals has been discussed
- One additional consideration is the effect of finite output bandwidth of the DAC or external components
  - Consider the *passive* losses of the DAC, not including the reconstruction waveform contributions
  - Additional losses may come from passive components (resistors, capacitors, inductors), PCB trace losses and transformer or balun losses
- The attenuation of these components add (in dB) to the reconstruction waveform and reconstruction filter responses to get the total output frequency response of the DAC and signal chain

Thanks for your time!