

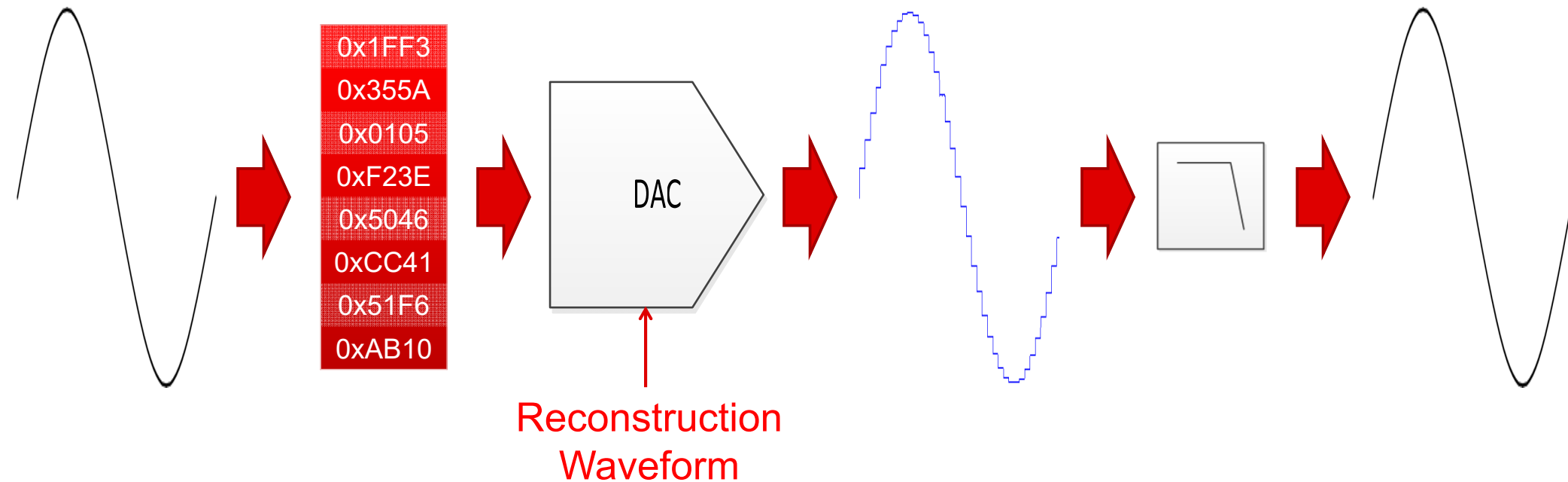
# Digital-to-Analog Converter (DAC) Output Response

TIPL 4705

Presented by Matt Guibord

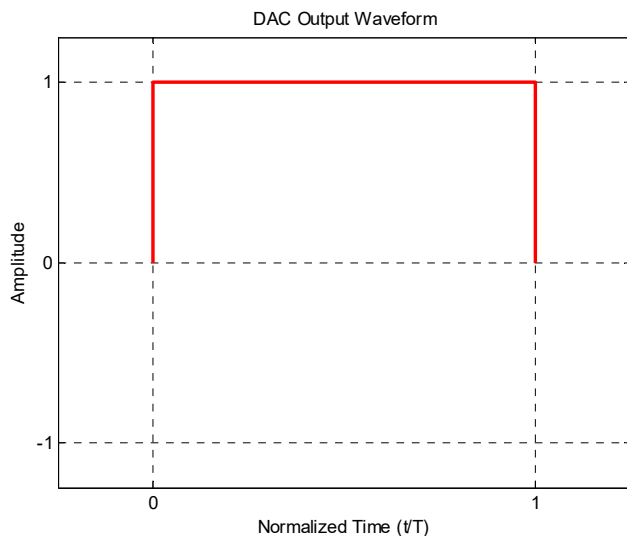
Prepared by Matt Guibord

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

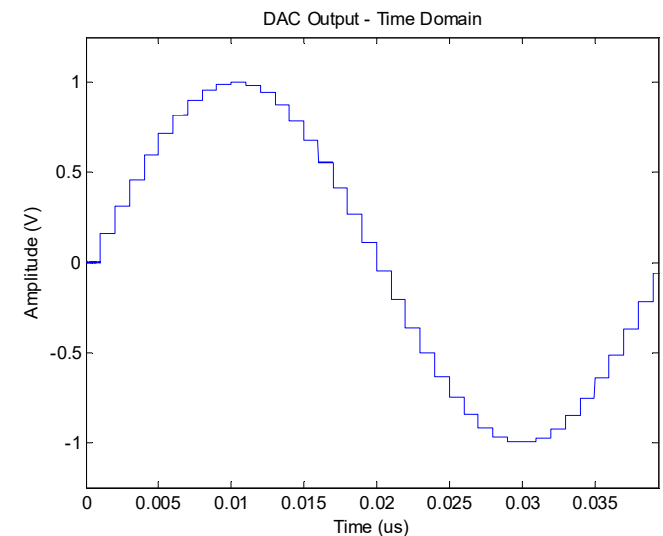


# Reconstruction Waveform – Time Domain

- 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

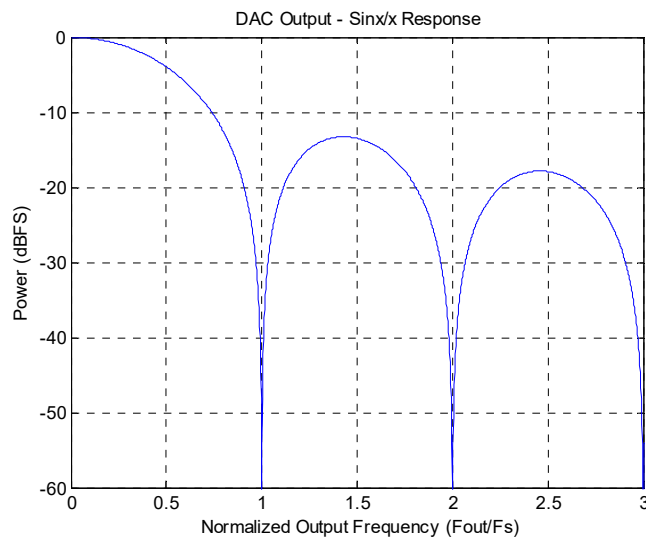


Weighted by  
digital samples

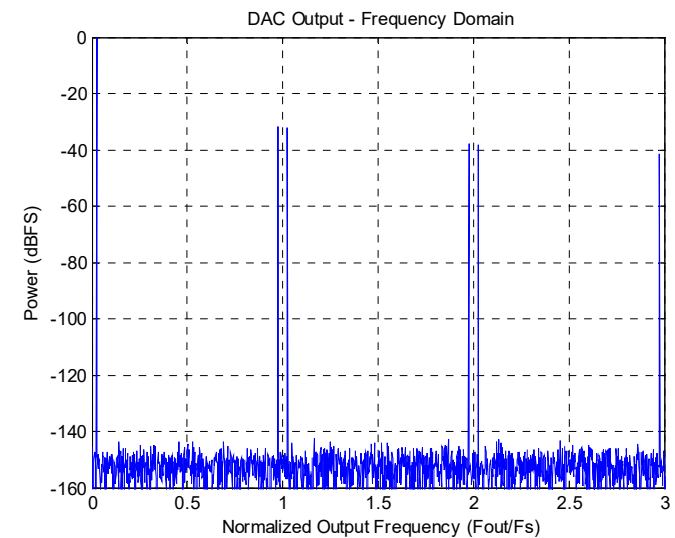


# Reconstruction Waveform – Frequency Domain

- 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

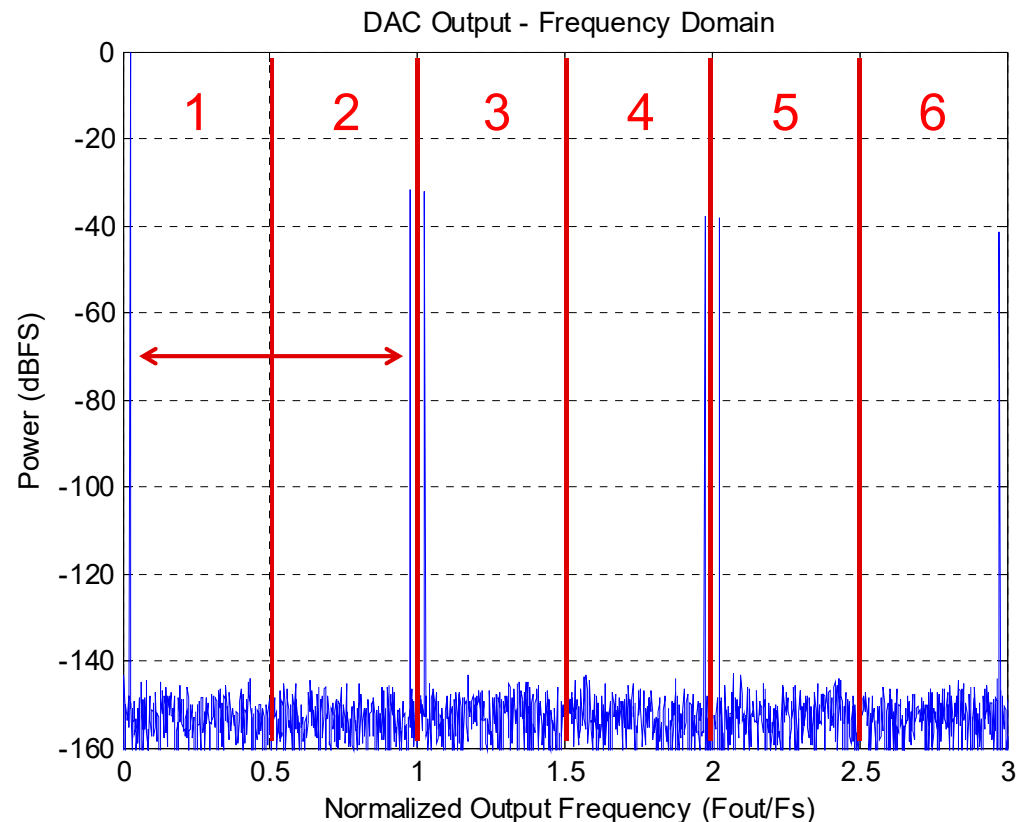


Weighted by  
digital samples



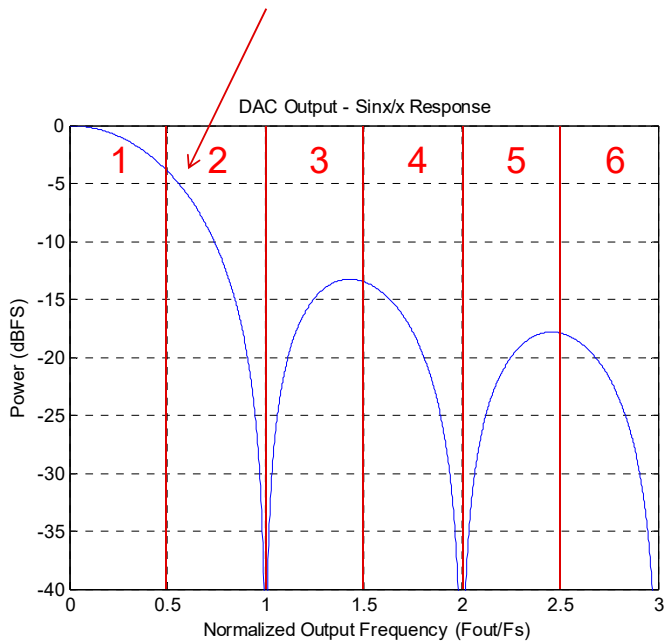
# What is a Nyquist Zone?

- A Nyquist zone corresponds to a band of frequencies  $F_s/2$  wide, where  $F_s$  is the DAC's sampling rate
- Each Nyquist zone is  $F_s/2$  wide, starting at DC:
  - The 1<sup>st</sup> Nyquist zone extends from DC to  $F_s/2$
  - The 2<sup>nd</sup> 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

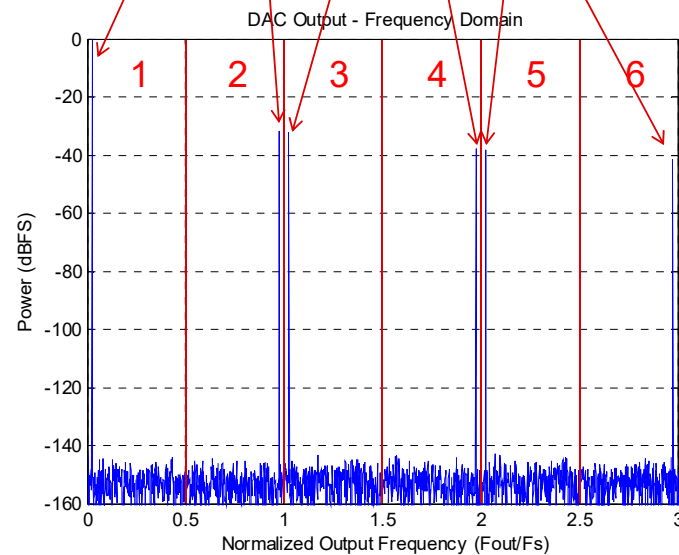
Loss of output power at higher frequencies due to sinc response



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

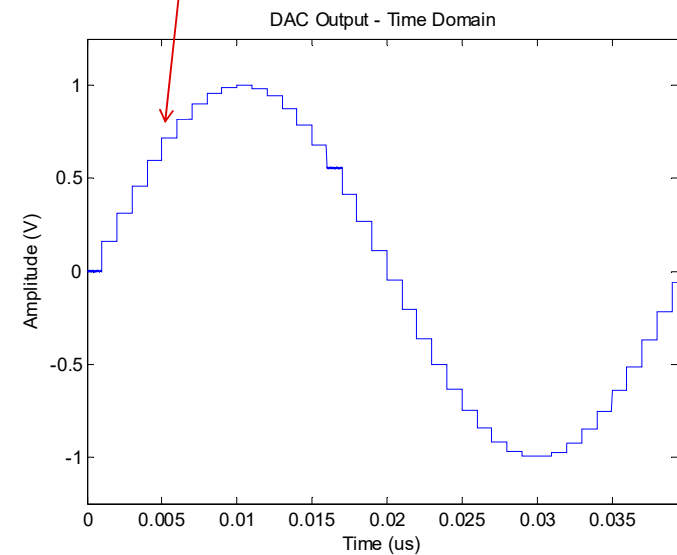
Images in other Nyquist zones must be filtered out

Desired signal



DAC Frequency Domain for Sine Wave Output and ZOH Reconstruction Waveform

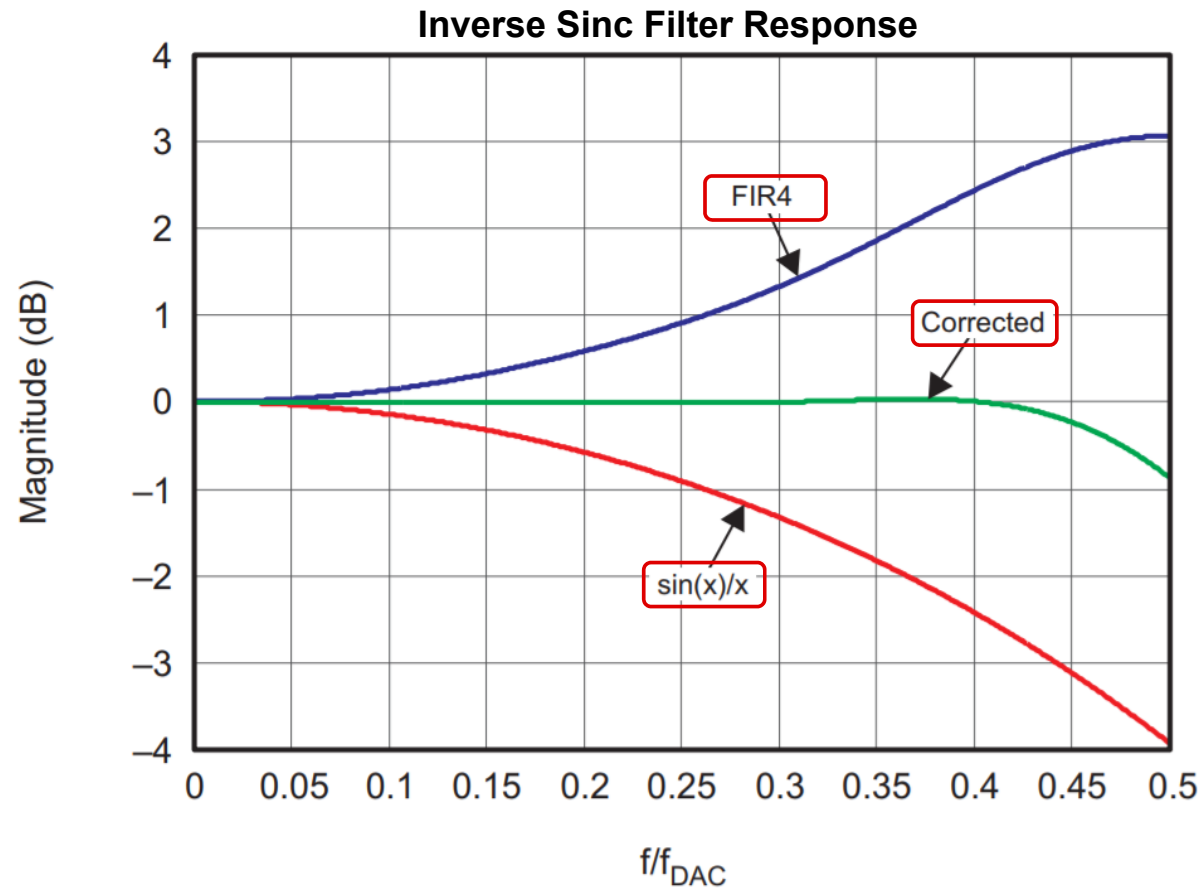
Images result in stair-case response in reconstructed waveform



DAC Time Domain for Sine Wave Output and ZOH Reconstruction Waveform

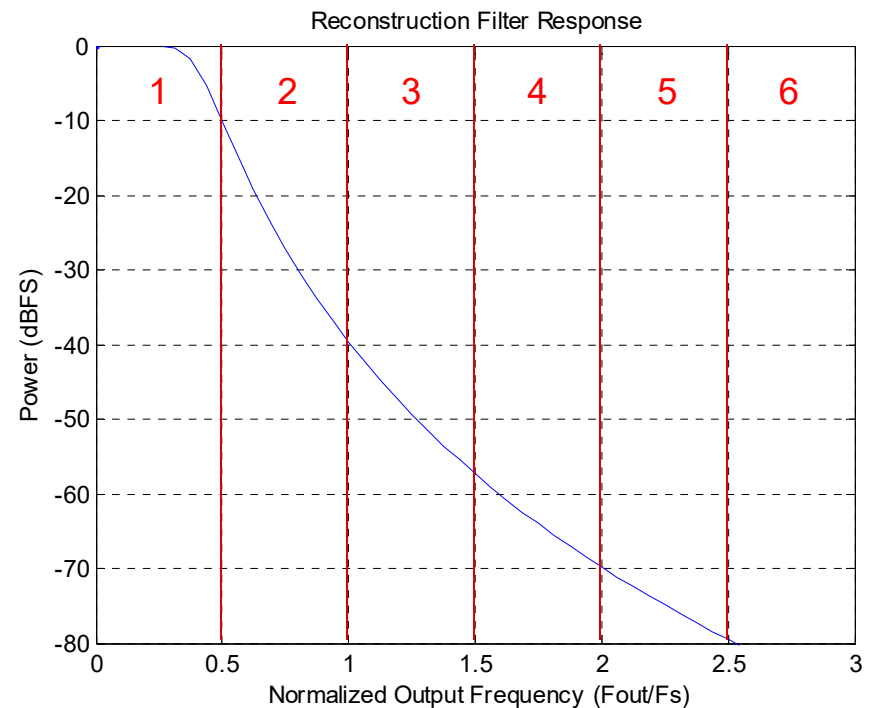
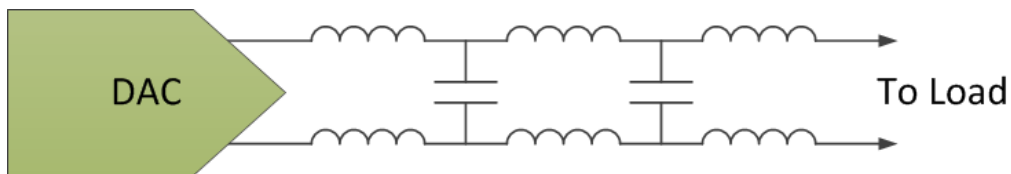
# Inverse Sinc Filter

- 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

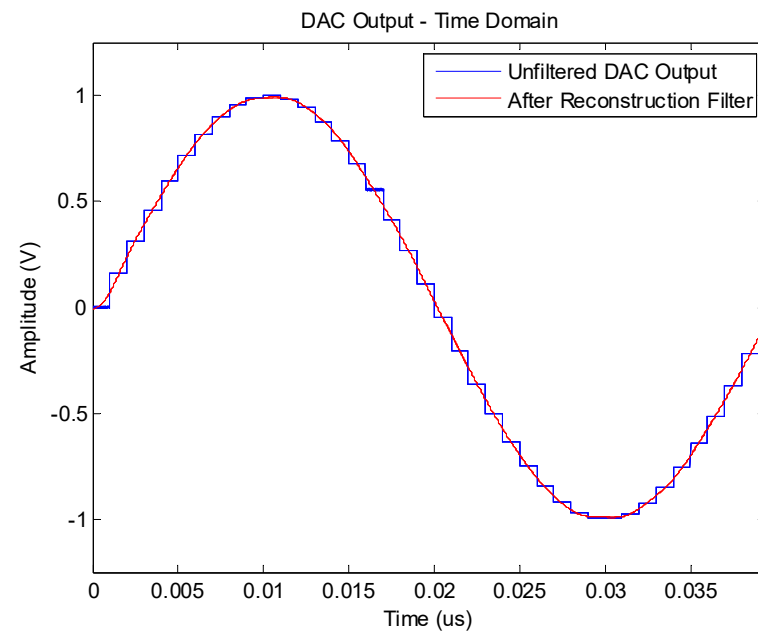
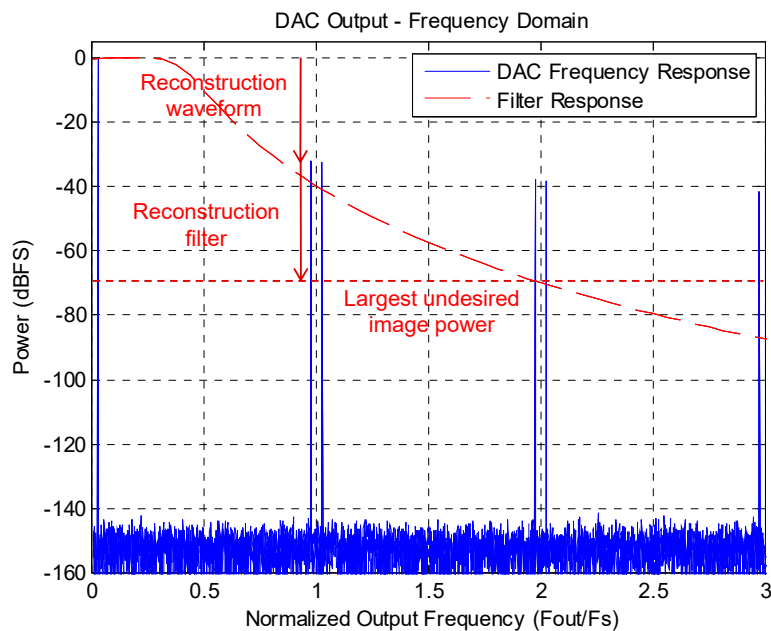
- An analog filter is required at the output of the DAC to select the desired image signal and attenuate the undesired images
- This analog filter is called a “reconstruction filter”
- An example (ideal) 5<sup>th</sup>-order low-pass Butterworth filter is shown with a cutoff frequency at 80% of the 1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





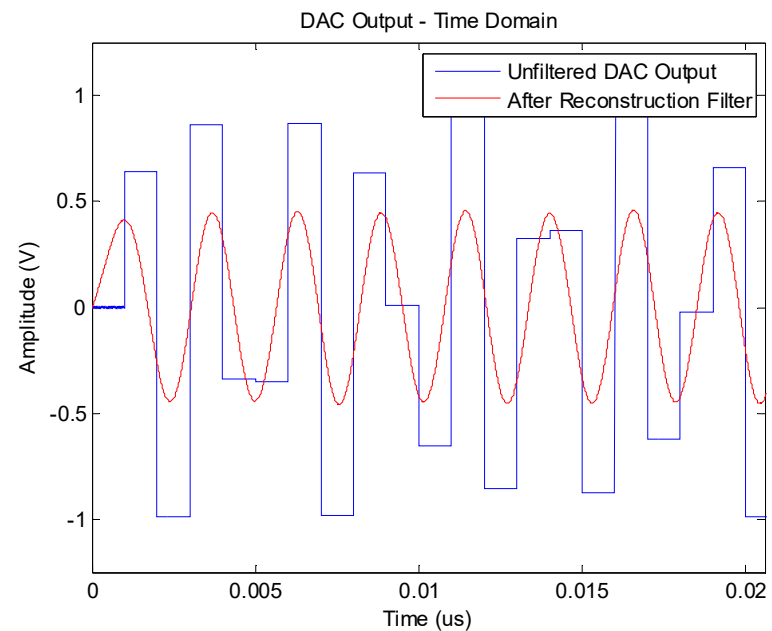
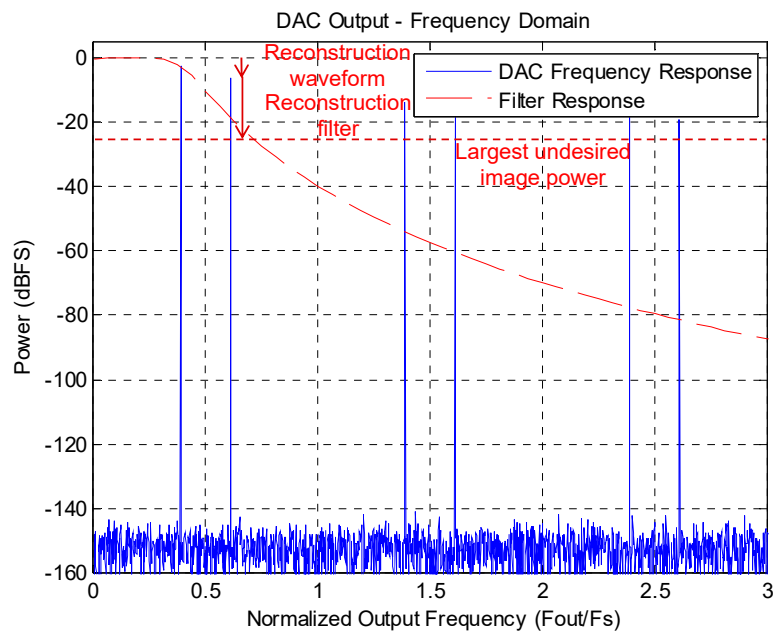
# Reconstruction Filter Example

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

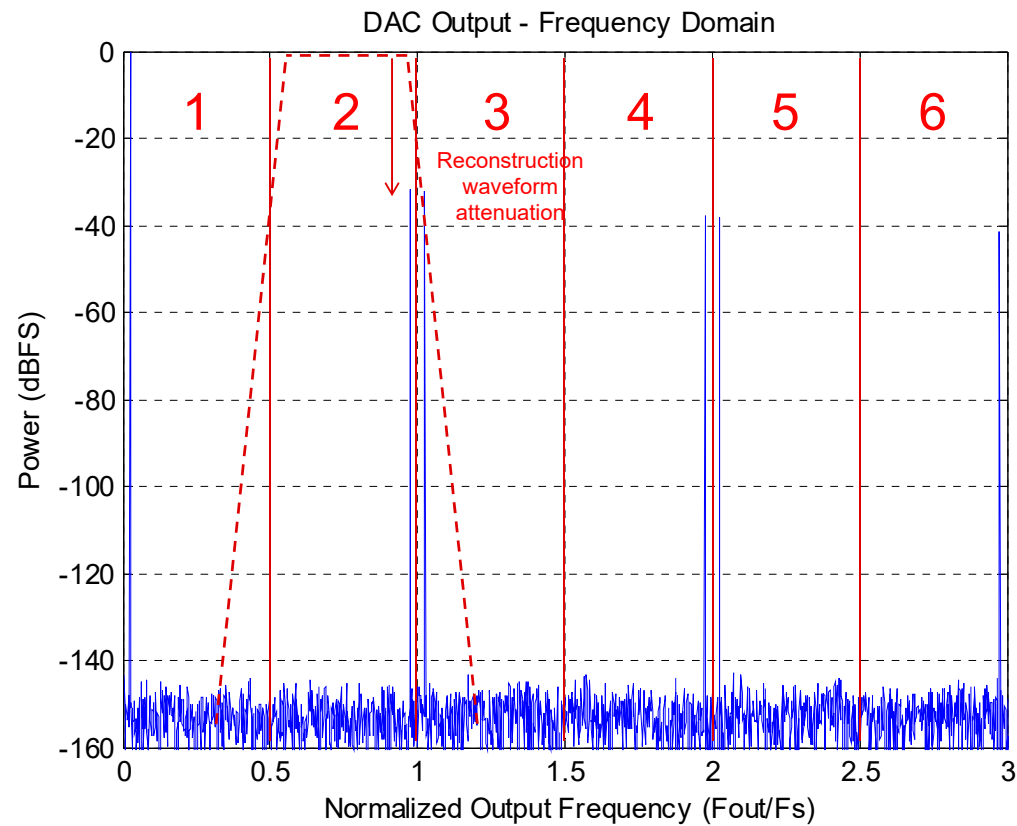


# Reconstruction Filter Example

- $F_S = 1$  Gsps,  $F_{OUT} = 400$  MHz
- Attenuation of 2<sup>nd</sup> 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?

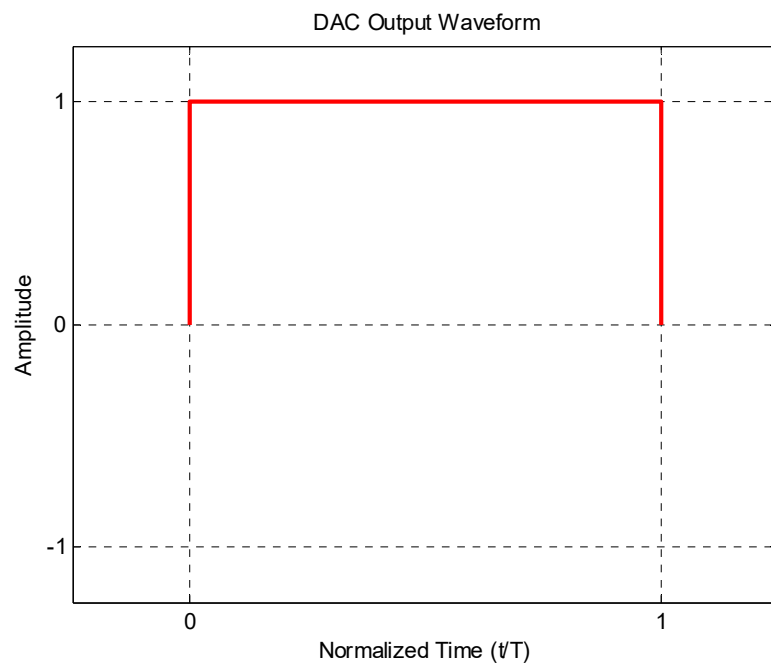


# Multi-Nyquist Modes

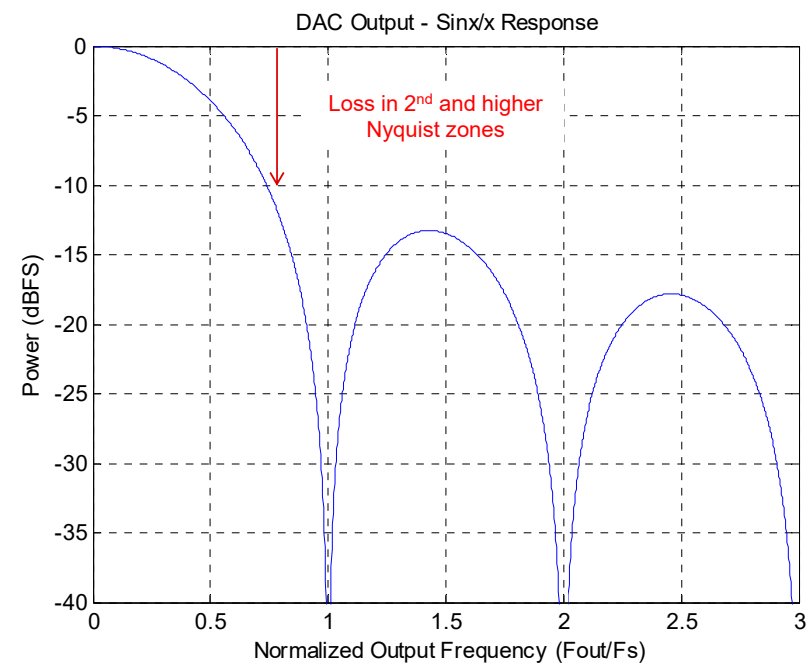
- The common ZOH reconstruction waveform results in a fairly flat response in the 1<sup>st</sup> Nyquist zone, but suffers from high loss in higher Nyquist zones
- If an alternate Nyquist zone image is desired, then a different reconstruction waveform should be used
- Common reconstruction waveforms:
  - Zero-Order Hold (ZOH) or Non-Return-to-Zero (NRZ) – 1<sup>st</sup> Nyquist only
  - Return-to-Zero (RTZ) – 1<sup>st</sup> and 2<sup>nd</sup> Nyquist
  - Return-to-Complement (RTC), also called Mixed Mode or RF Mode – 2<sup>nd</sup> and 3<sup>rd</sup>
- 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

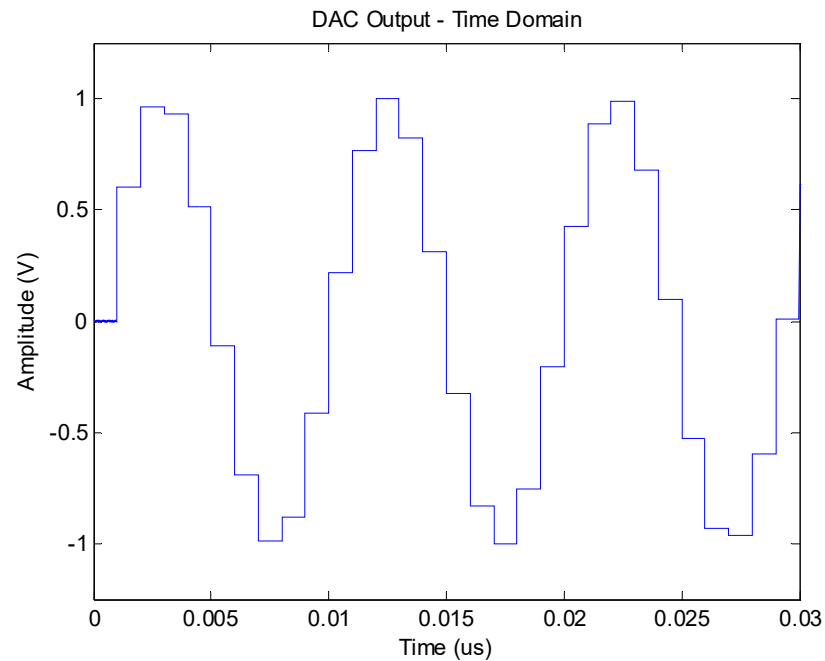


## Frequency Response

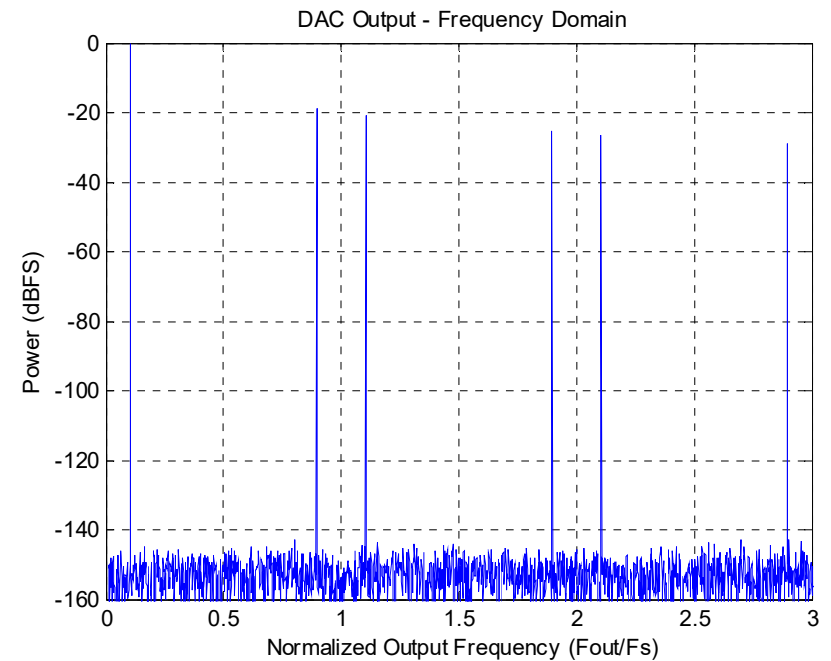


# Zero-Order Hold (or Non-return to Zero, NRZ)

## Time Domain Waveform

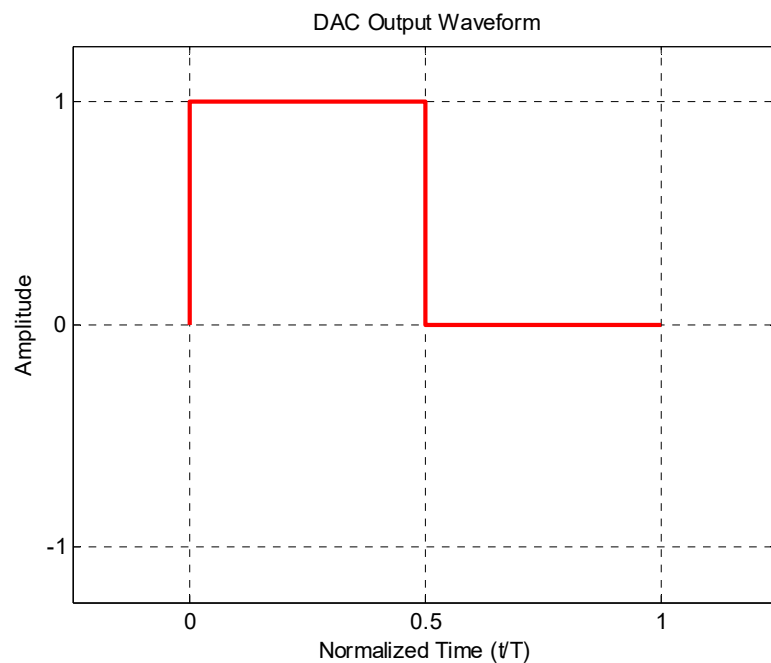


## Frequency Domain

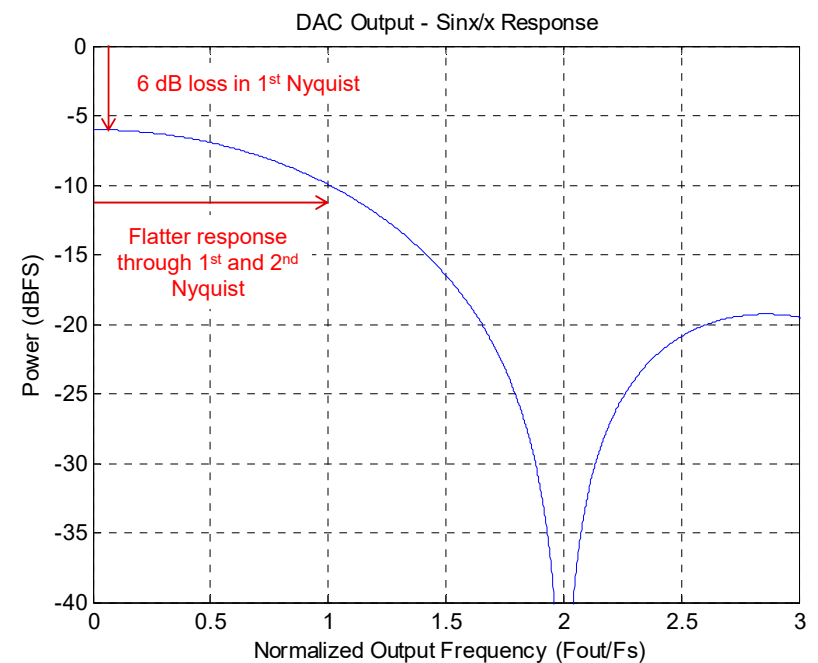


# Return-to-Zero (RTZ)

## Reconstruction Waveform

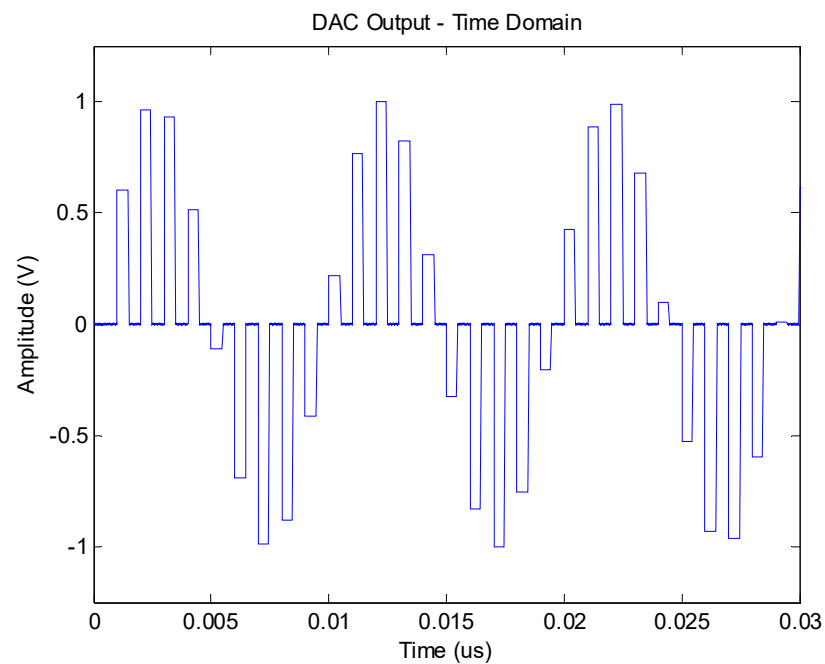


## Frequency Response

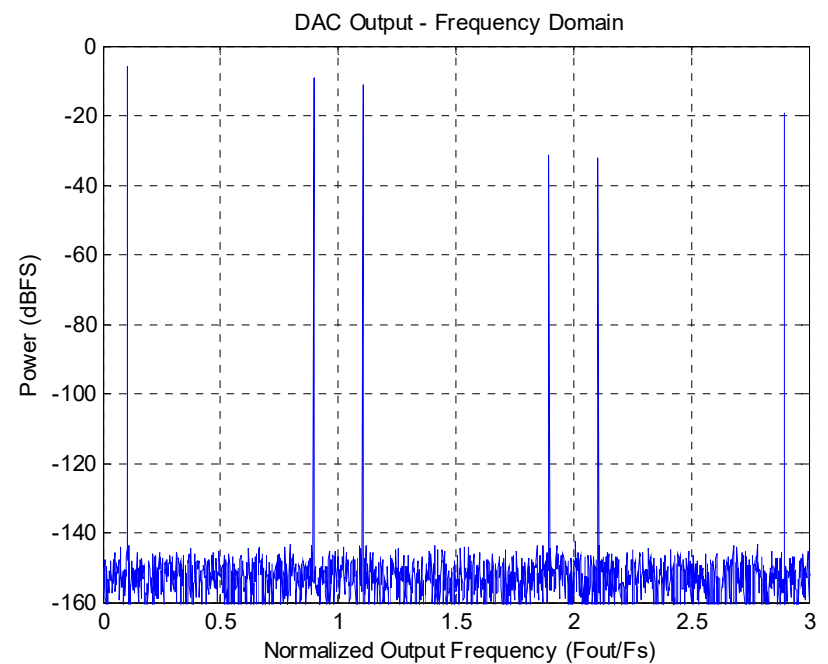


# Return-to-Zero (RTZ)

## Time Domain Waveform



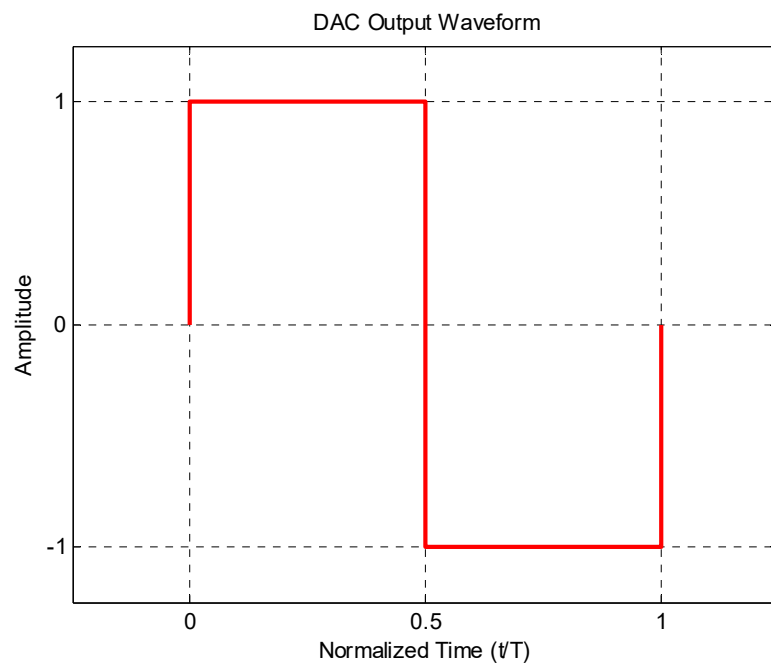
## Frequency Domain



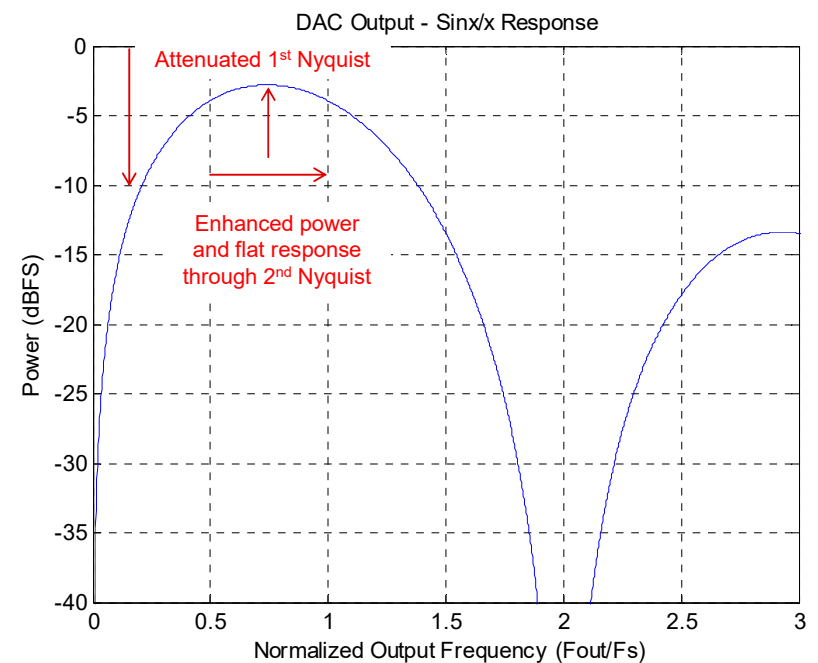


# Return-to-Complement (RTC) or Mixed Mode

## Time Domain

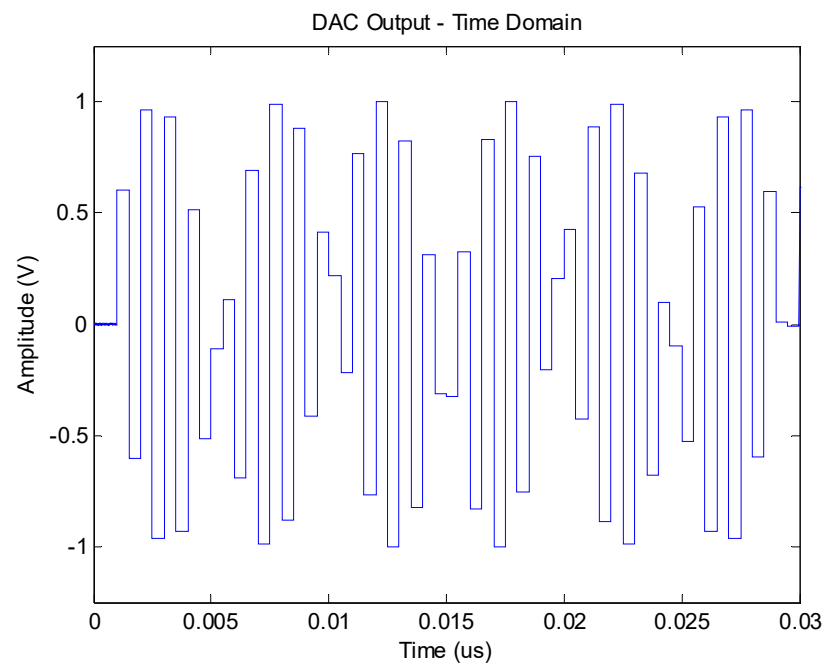


## Frequency Domain

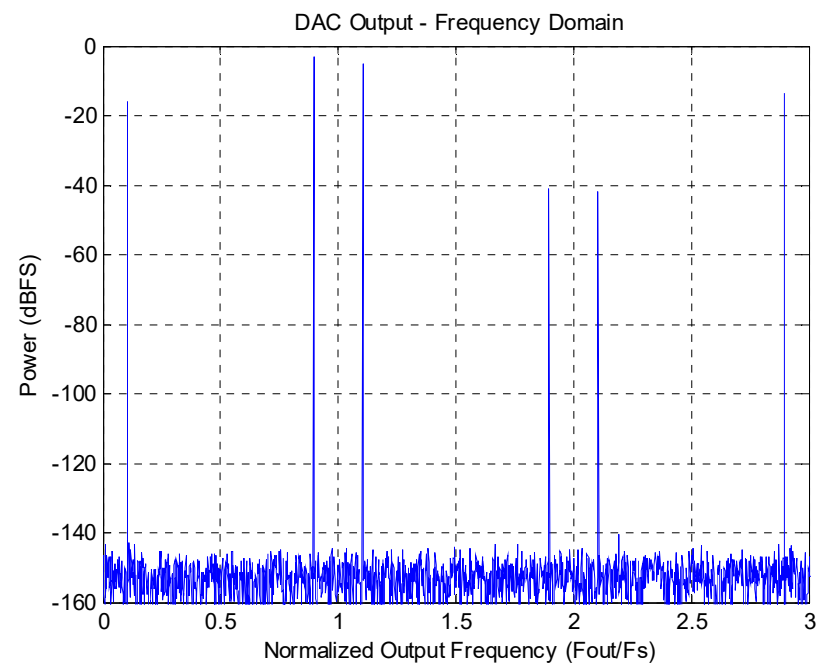


# Return-to-Complement (RTC) or Mixed Mode

## Time Domain Waveform

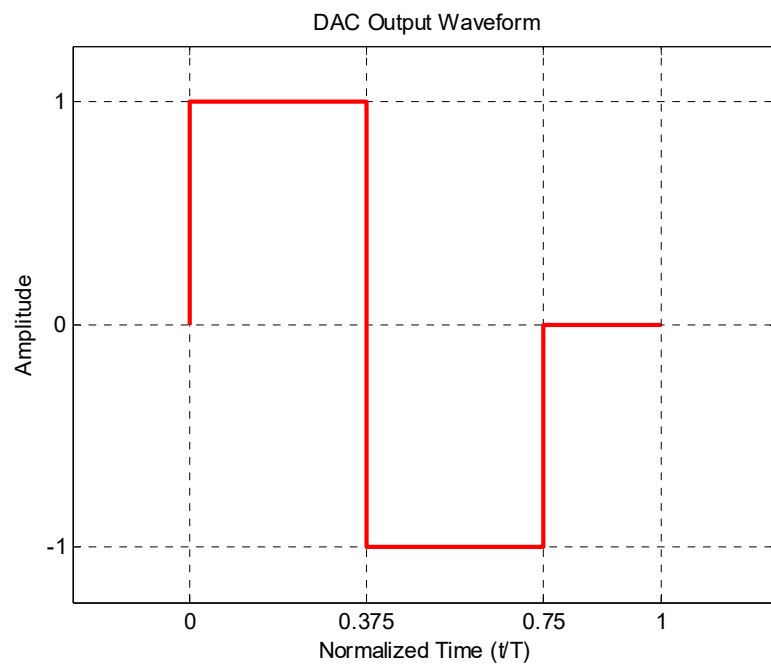


## Frequency Domain

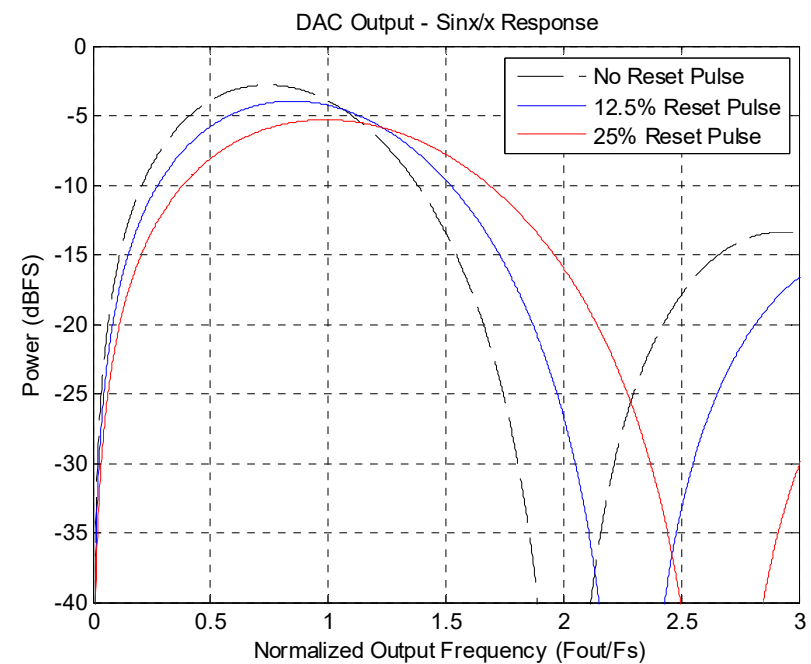


# Return-to-Complement with Reset Pulse

## Time Domain

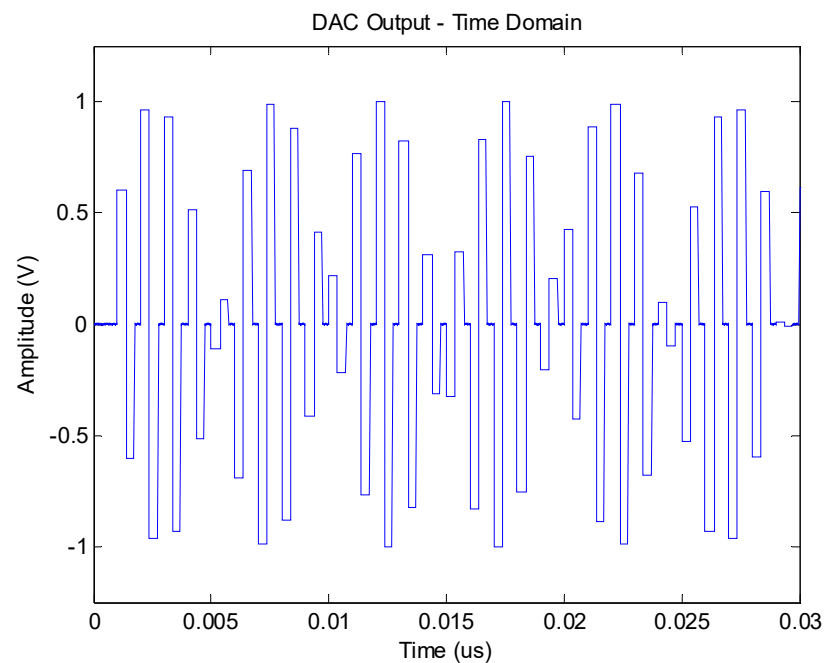


## Frequency Domain

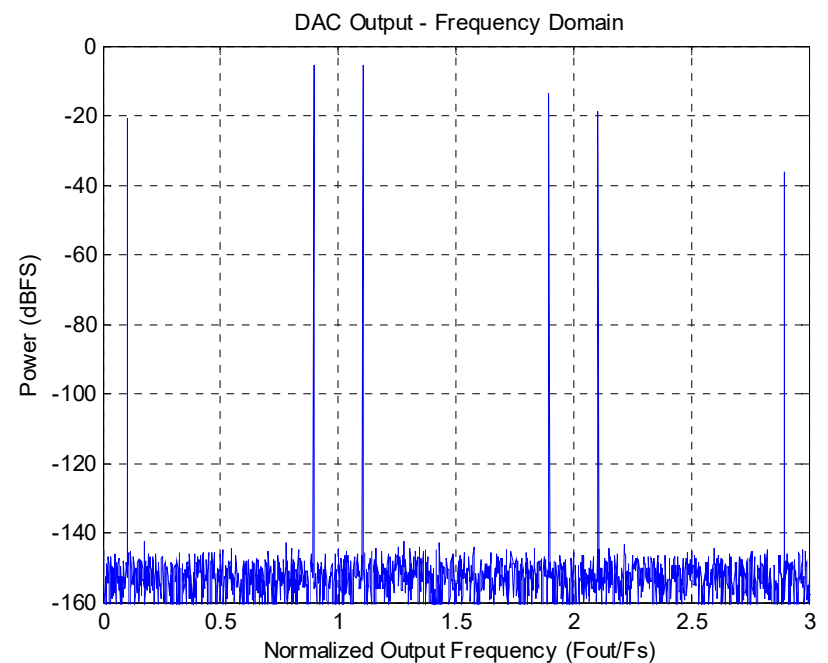


# Return-to-Complement (Mixed Mode)

## 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!



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