

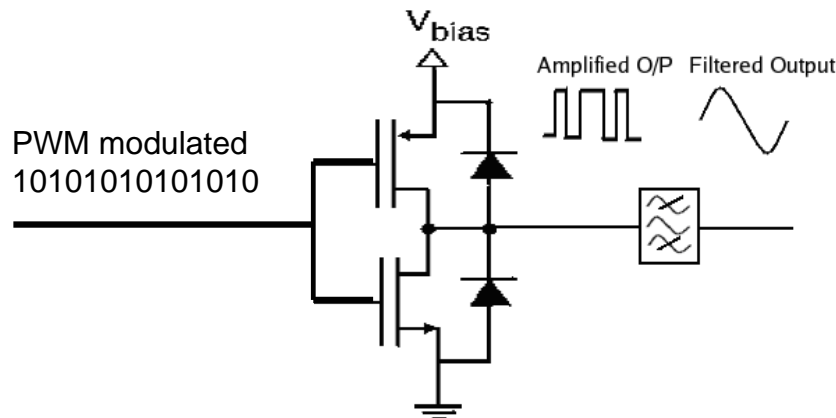
# Using High Pass Sigma-Delta Modulation for Class-S Power Amplifiers

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- Introduction
- Use of  $\Sigma\Delta$ M in Power Applications
- Review of Sigma-Delta Modulators ( $\Sigma\Delta$ M)
- Requirements for Communications Applications
- Benefits and Challenges of Using a High-Pass Modulator
- Conclusions

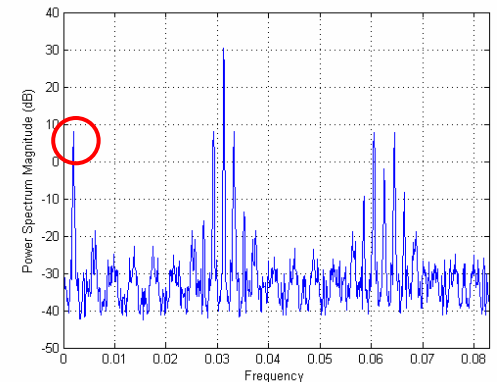
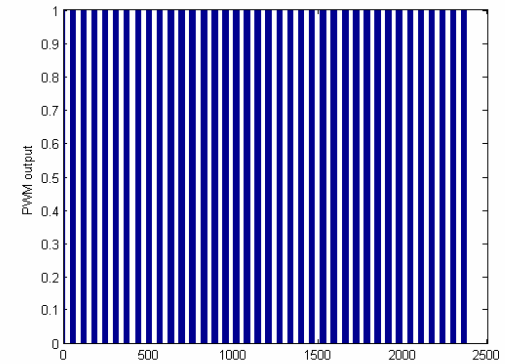


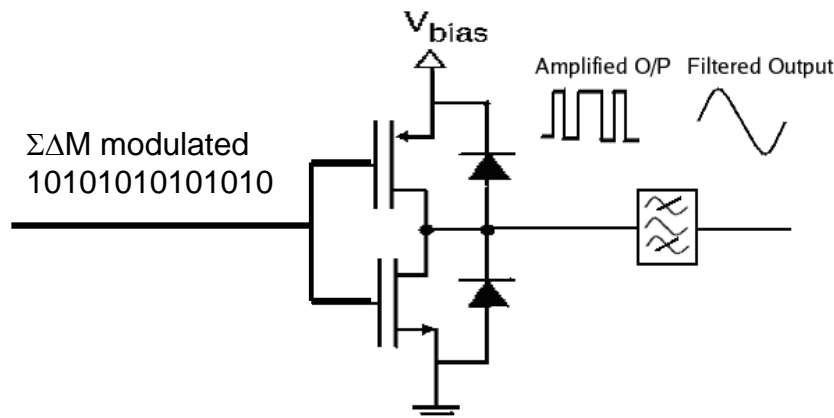
A voltage switch will convert 1/0 values into voltages, preserving the spectral information, irrespective of the voltage levels.

Two voltage levels (on/off) **guarantee perfect linearity**

With ideal switches, the voltage-current product is always zero, **providing 100% efficiency** in the conversion

PWM signals result in **large harmonic distortion** and relatively **poor noise** performance

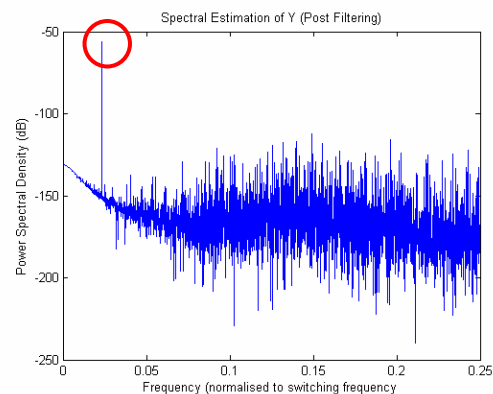
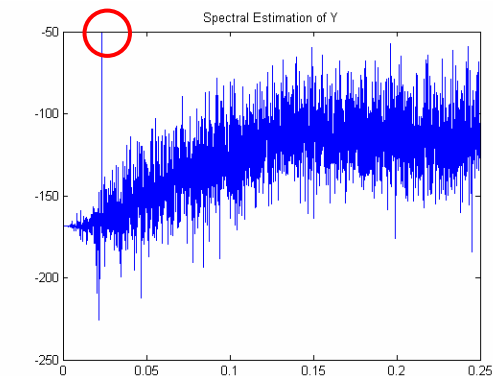
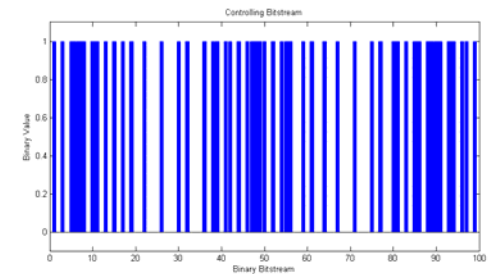


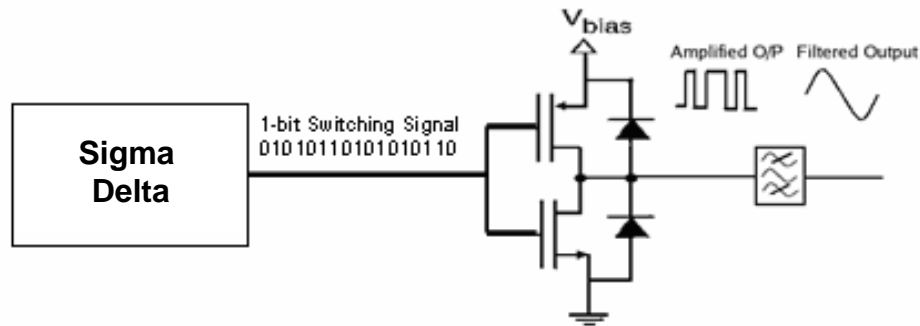


Sigma-delta modulation ( $\Sigma\Delta$ M) generates a “pulse density modulated” binary output

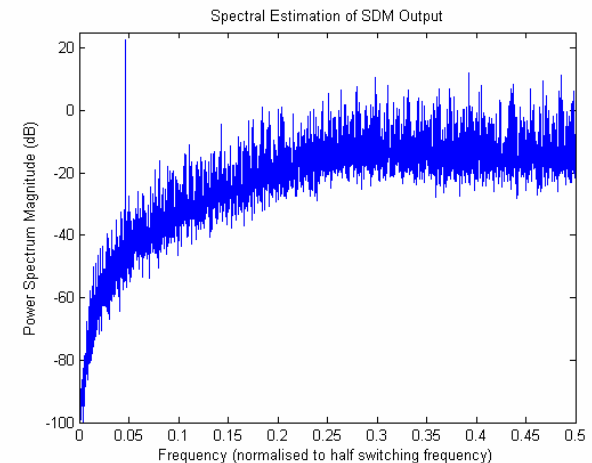
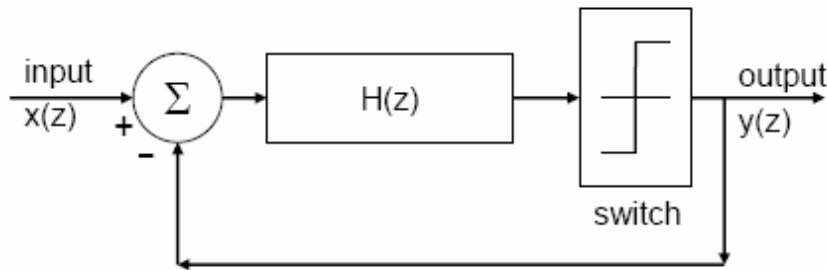
In power applications it has the same benefits of linearity and efficiency as PWM.

It has **immensely superior noise** and distortion performance for a system with the same switching frequency as PWM



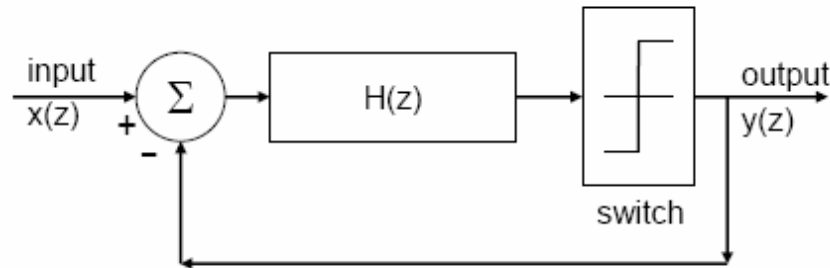


- At audio frequencies, such a system would be called a sigma-delta modulated **digital-to-analog converter (DAC)**
- If then used with a power switch, it's called a **Class-D (digital) PA**
- At RF frequencies, some people call it a **Class-S (sigma-delta) PA**
- It could equally be called a **power-DAC**.



Sigma-delta modulators are a control loop, with a narrow bandwidth, high resolution input and a low resolution, wide bandwidth output

- Within the passband of  $H(z)$  the spectral characteristics of the output and input are maintained the same, due to the feedback loop.
- Within that narrow pass band, in-band noise may be minimised at the expense of out-of-band noise
- Three flavours, depending on  $H(z)$ : **Lowpass, Bandpass, Highpass**

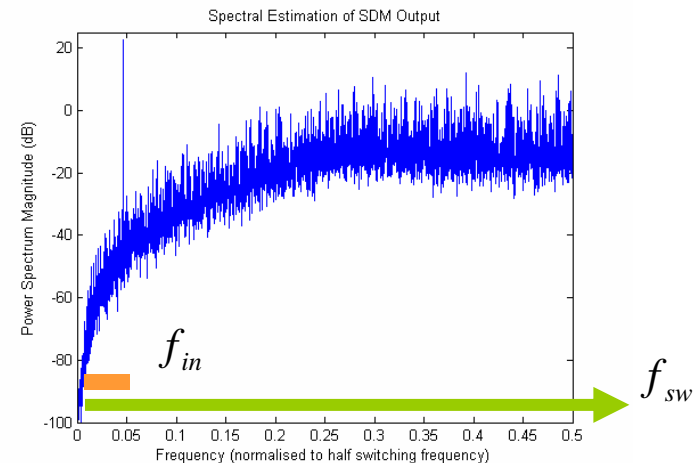
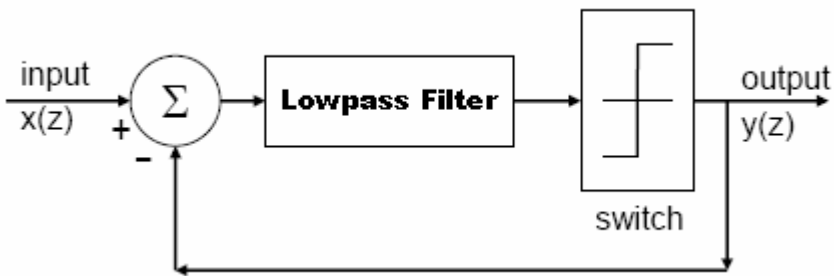


The shape of the noise floor is dependent on

- The order of the loop filter
- Scaled proportionally to the **switching frequency**

The ratio between the signal bandwidth and the switching frequency is called the **oversampling ratio (OSR)**

To achieve a certain noise performance, the OSR must exceed a certain level, depending on the order of the loop filter.



A very common system is the second order system with

$$STF = z^{-2}$$

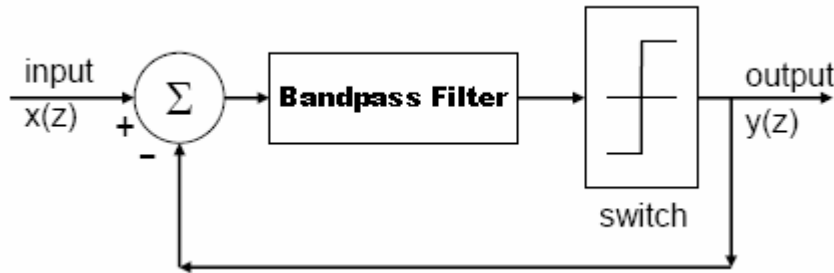
$$NTF = \frac{1}{(1 - z^{-1})^2}$$

The noise notch is at dc, and rolls off at 20dB/decade per order of the filter. To get a very low noise, we need to stay close to dc, ie the signal bandwidth must **be a small fraction of the switching frequency** (a high OSR)

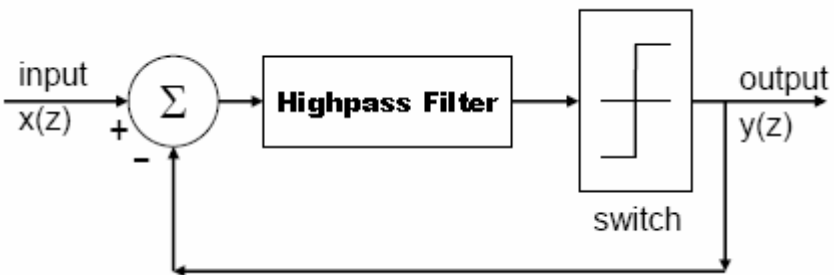
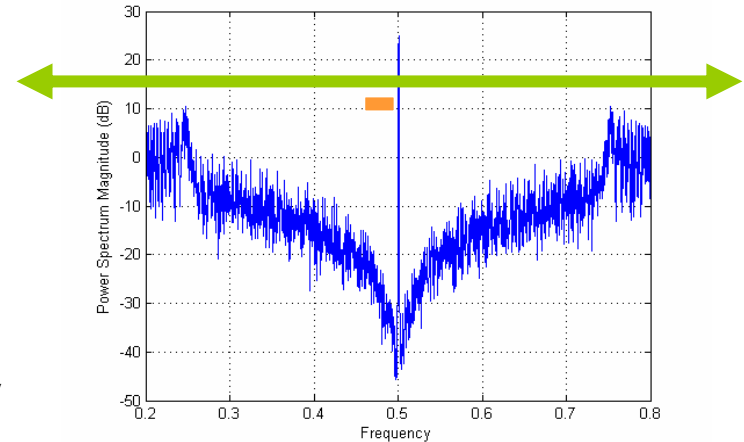
Typically restricted to low frequency applications due to OSR issues

$$OSR = f_{in} / f_{sw}$$

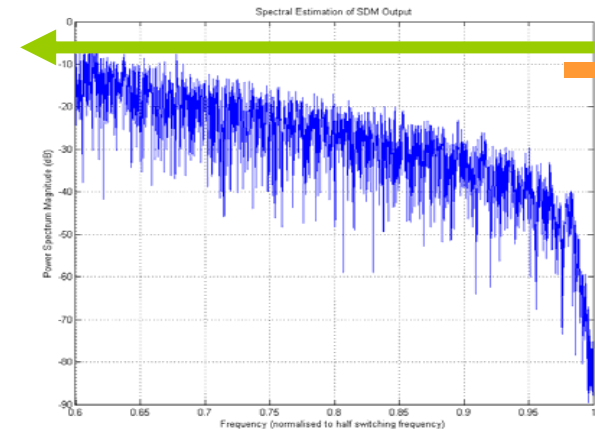


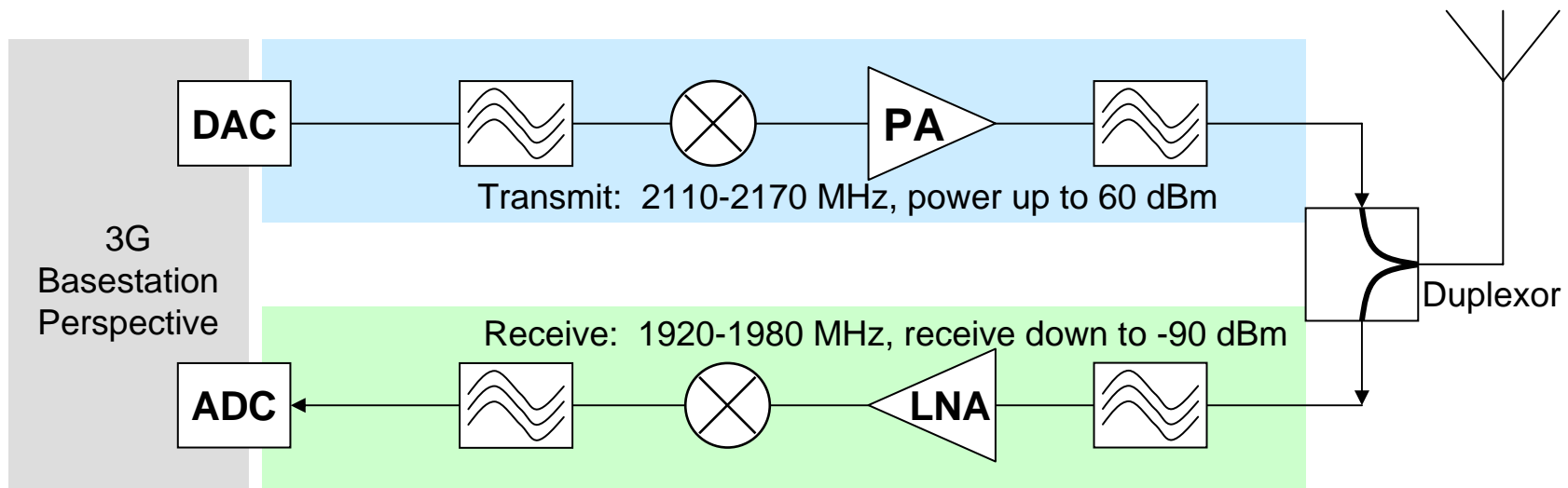


Passband now at  $\frac{1}{4}$  the switching frequency  
Complex transfer function for modulator  
Oversampling ratios (OSR) are **large**



Passband now at  $\frac{1}{2}$  the switching frequency  
Structure of modulator **remains the same**  
Oversampling ratios (OSR) are **large**



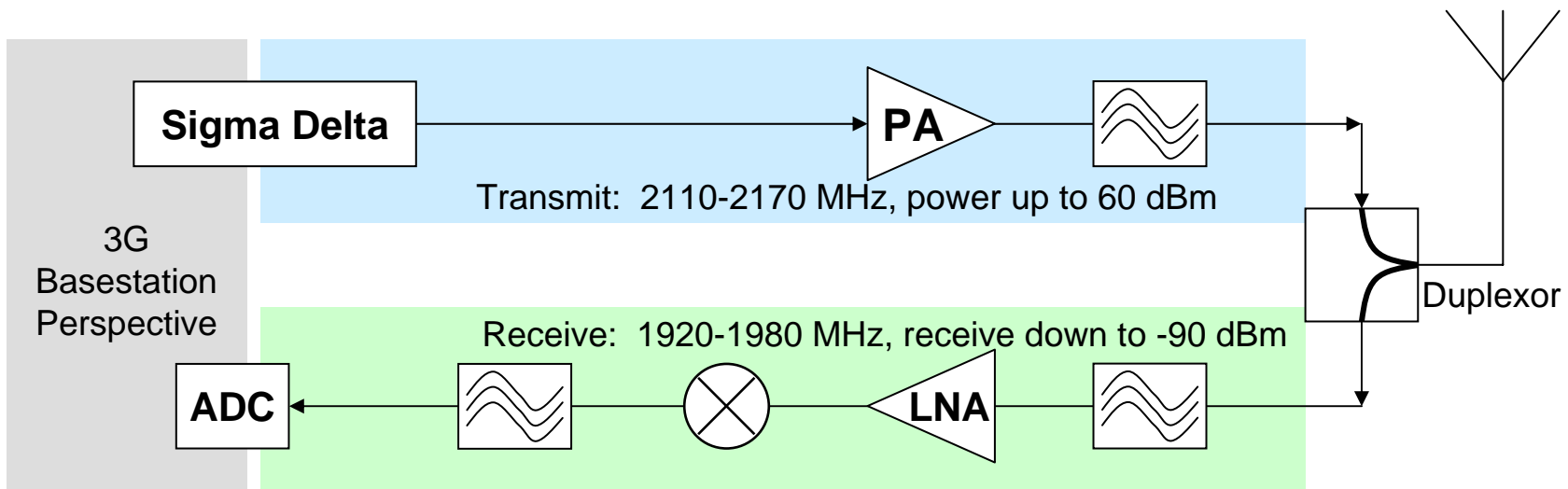


Many systems (3G), for example, using frequency-division multiplexing

A very big issue in 3G basestations is that the duplexor can leak power from the transmit path to the receive path. The duplexor must provide >150 dB of isolation.

Transmitt SNR is less important (60 dB would be enough)

It is important that transmit noise is minimised in the receive band, without the use of additional filtering.

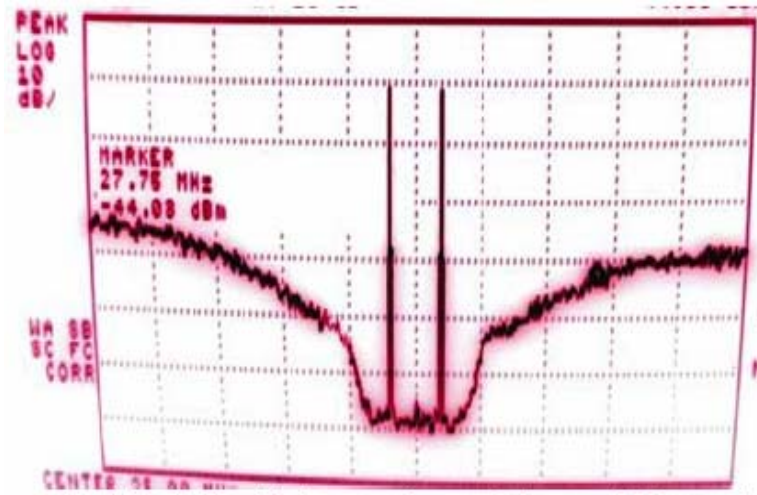


A Class-S power-stage would avoid the need for  
DACs,  
Mixers  
traditional PAs

However existing bandpass solutions require excessively high switching speeds...

**a highpass system will do the job at half the frequency  
allowing us to use existing silicon technology**

# One Small Problem...



High-Pass systems have an immediate reflection just above  $f_{sw}/2$ ,

This image is adjacent to our signal band and very difficult to filter away

However if we use a switching frequency where  $f_{sw}/2$  is a bit higher than where we wish, it is possible to spread the two images apart.

$$f_{sig} = 1920 \text{ MHz}$$

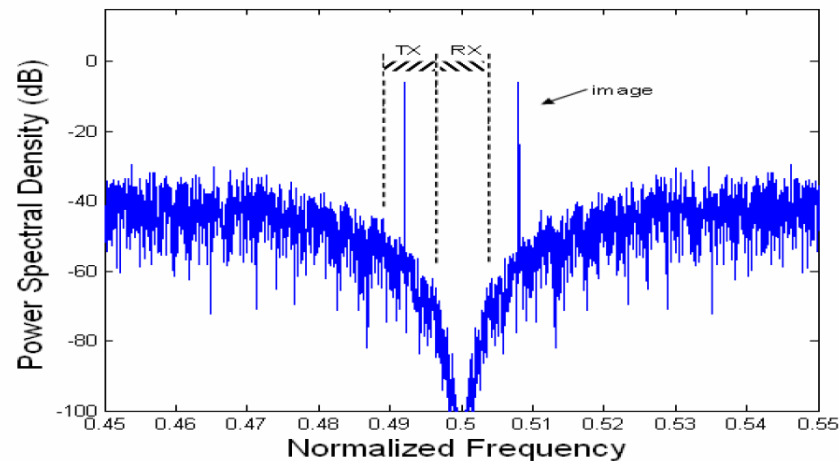
$$f_{sw} = 1970 \text{ MHz}$$

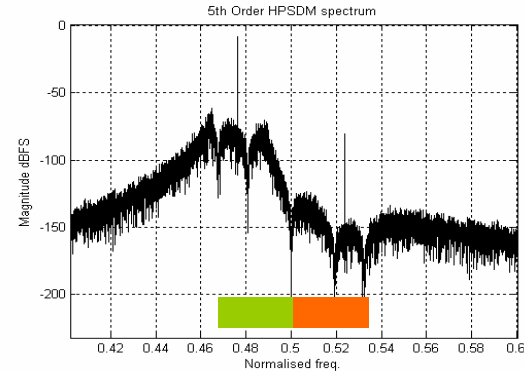
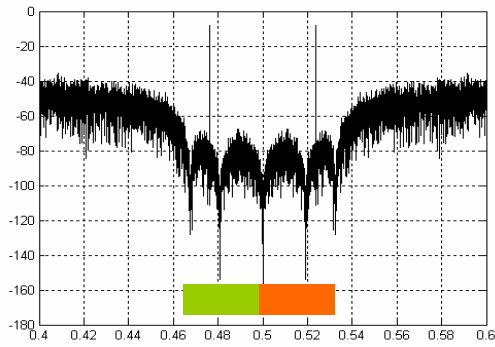
$$f_{upper} = 1920 \text{ MHz} \quad (f_{sw} - 50)$$

$$f_{lower} = 2020 \text{ MHz} \quad (f_{sw} + 50)$$

This will make filtering the two images much easier.

We can place the notch in the RX band preventing noise passing through duplexor.





The notch is  $\pm 3\%$  of  $F_s/2$

(For a 1.8 GHz  $F_s/2$ , this gives a signal bandwidth of  $\sim 54$  MHz)

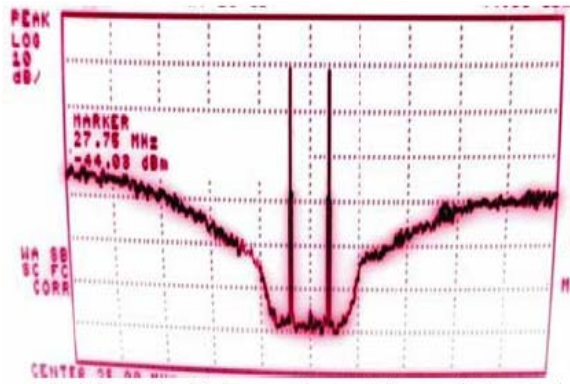
Using a more complex filter in the modulator, the NTF can be altered to trade depth for width.

We can choose to

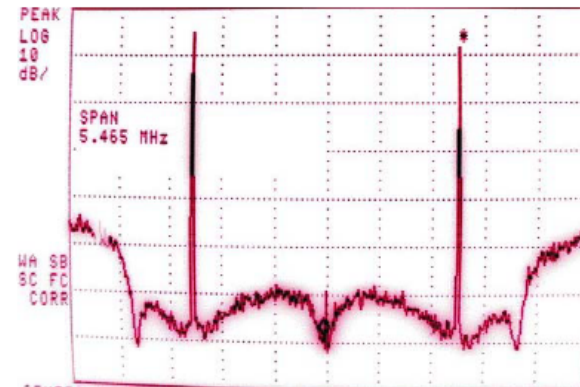
- reduce the transmit in-band noise
- reduce the transmitter noise in the RX band.

Highpass and low-pass modulators are highly amenable to NTF sculpting.

To prove the concept of highpass sigma-delta modulation various digital modulators were designed and the prototypes were tested in a Xilinx FPGA at a sampling frequency of 50MHz



Separation = ~2% of  $F_s$

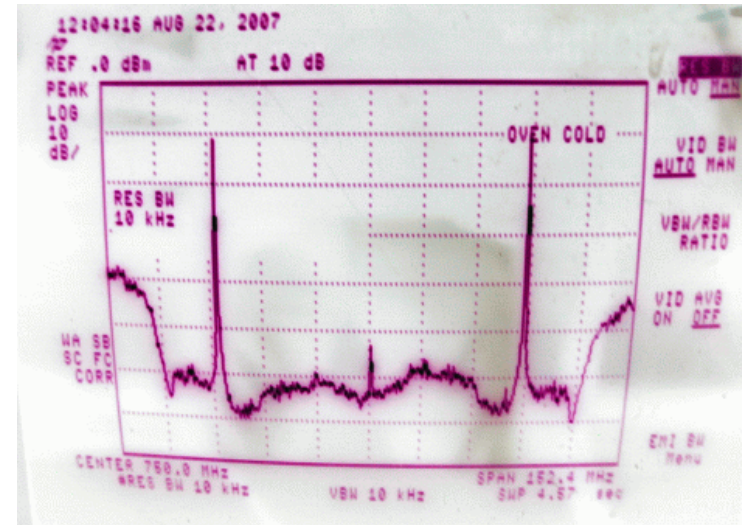
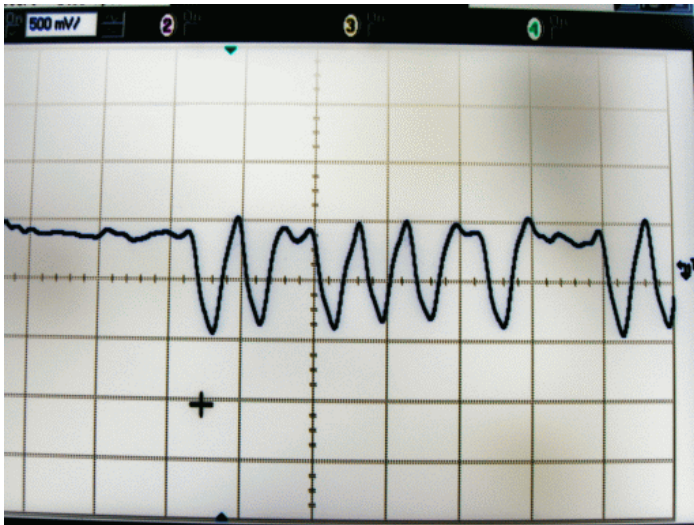


Separation = ~10% of  $F_s$

The first modulator above is designed to have narrow noise notch with the signal and its image close to one another

The second modulator above has a much wider noise notch. This allows the signal to be located further back from  $f_{sw}/2$ , which eases the removal of the signal image

Just recently we have provisional results from a 1.5 GBPS RocketIO port on a Xilinx Virtex 2 FPGA



- a noise notch at 750 MHz,
- with a noise floor at -60 dB
- image separation of 90 MHz
- expectation of improvement in noise with a better switching circuit.