A Baseband Pulse Shaping Filter for Gaussian Minimum Shift Keying

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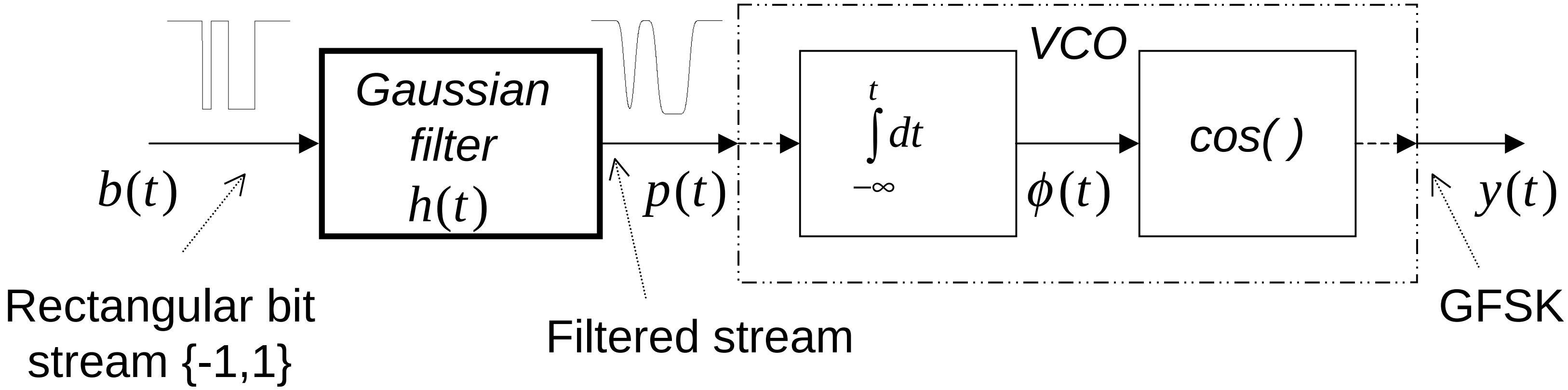
Motivation

- Rectangular bit stream has a large amount of energy at high frequencies.
- Pulse shaping limits the out of band radiation in communication systems.
- Digital pulse shaping - harder with high bit rates.
- Analog pulse shaping → lower power and area?

Pulse shaping



$b(t)$

Gaussian filter $h(t)$

$p(t)$

VCO

$\int_{-\infty}^{t} dt$

$\phi(t)$

cos( )

$y(t)$

Rectangular bit stream {-1,1}

Filtered stream

GFSK

$$\boxed{p(t) = h(t) \otimes b(t)}$$

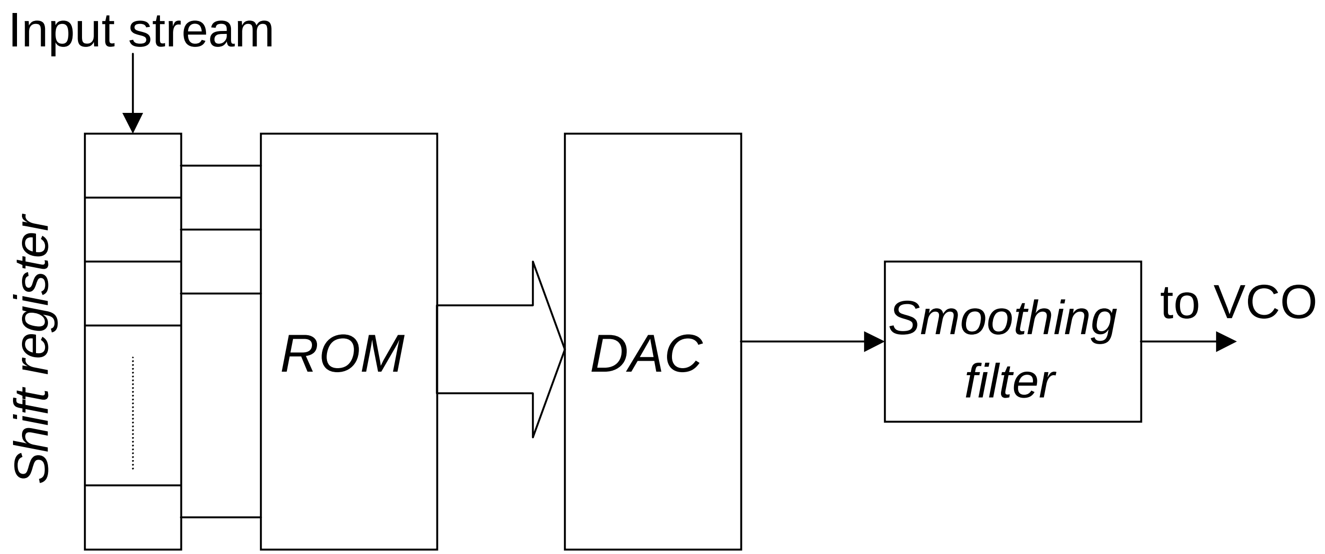
- $h(\ )$: gaussian impulse response.
- $b(\ )$: rectangular pulse train.
- $p(\ )$: smoothed (gaussian filtered) pulse train.

Pulse shaping

$$\boxed{h(t) = B\sqrt{\frac{2\pi}{\ln(2)}}\exp\left(-\frac{2\pi^2 B^2 t^2}{\ln(2)}\right)}$$

- $h(\ )$: Non-causal and infinitely long. Truncated and shifted in practice.
- B: -3dB bandwidth of the gaussian filter.
- Pulse shape characterized by "BT_b" product. T_b is the bit period.
- Pulse width increases as "BT_b" decreases - higher truncation length.

Digital pulse shaping



- Store the values of the oversampled pulse shape(unit step response) in a ROM.
- Read out into a DAC.
- Filter the staircase waveform using a continuous-time filter.

Digital pulse shaping

- DAC:
  - * 6 - 7 bits.
  - * Power hungry for large sampling rates.
- ROM
  - * 6 - 7 bits x Oversampling ratio x N.
  - * N = 2^(no. of bit periods in the unit step response).
- Smoothing filter:
  - * Linear phase in order not to distort the pulse shape.
  - * Trivial for low bit rate / high oversampling rate (e.g. 1st order RC).
  - * High order for small oversampling rates (e.g.: 6th order for OSR=6).
  - * Tuning may be required.
  - * Cutoff frequency > B, where B is the bandwidth of the pulse shape.

Analog pulse shaping?

Direct implementation of the convolution

$$p(t) = h(t) \otimes b(t)$$

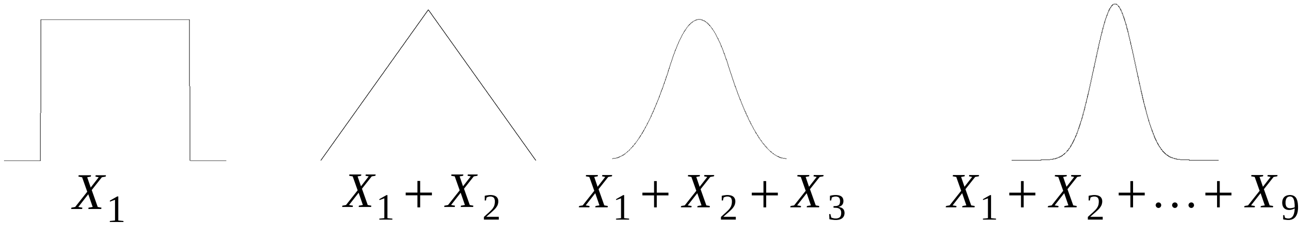
using a filter with an impulse response $h(\ )$

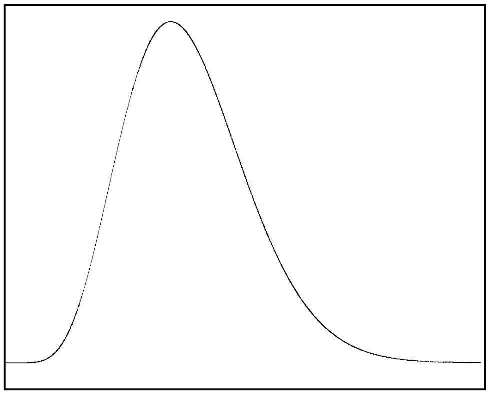
- How to obtain a gaussian impulse response?
  - * A cascade of a large number of filters with positive impulse responses has a gaussian impulse response. (“Central Limit Theorem”).
  - * Gaussian magnitude response + linear phase → gaussian impulse response.
  - * Bessel filter: optimized for linear phase.

∴ Use a high order Bessel filter!

Analog pulse shaping

- The central limit theorem
  - $X_1, X_2, \ldots, X_n$: i.i.d random variables $\Rightarrow$ $X_1+X_2+\ldots+X_n$ has a gaussian probability density function if n is very large.
  - e.g. $\{X_i\}$: uniformly distributed.



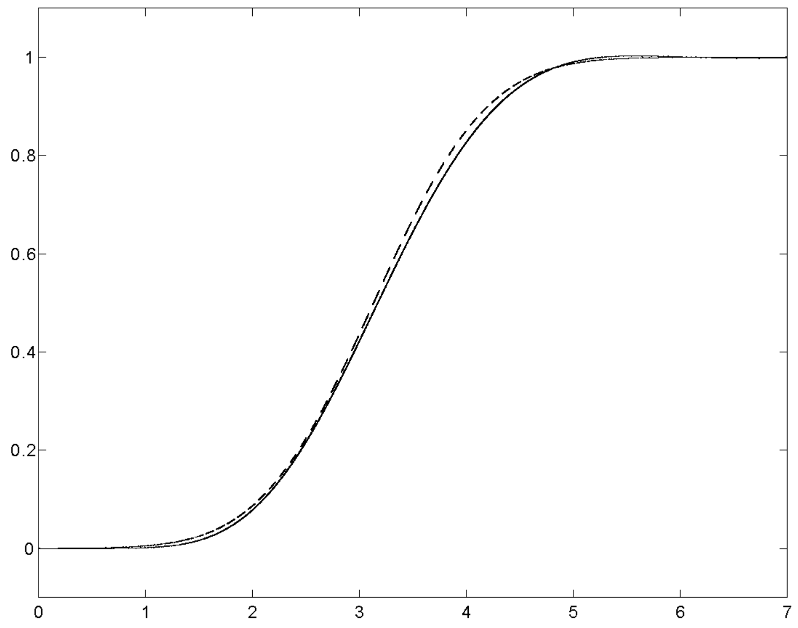


Response of a cascade of 8 buffered 1st order RC sections

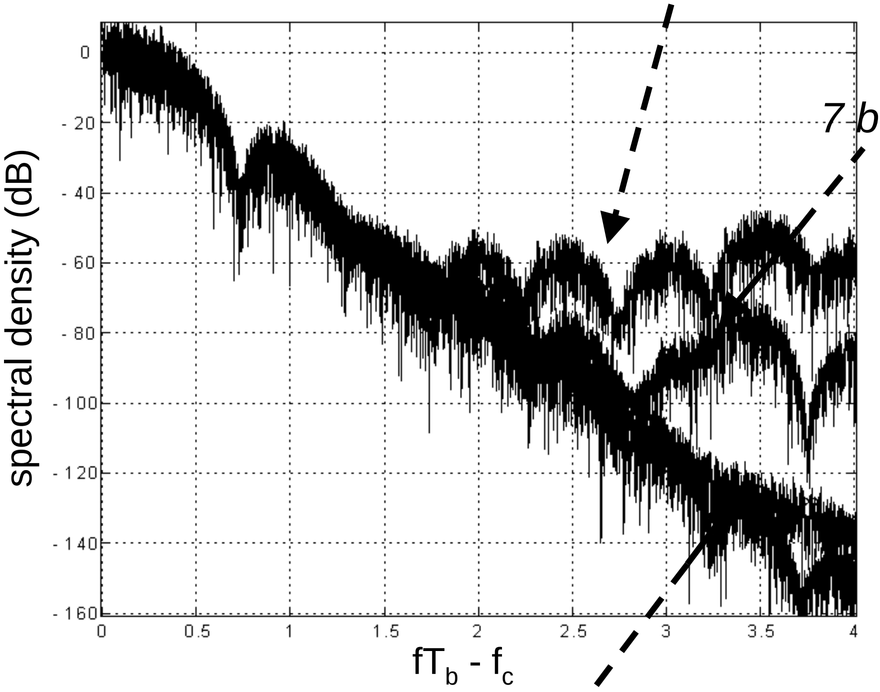
Feasibility

- 8th order Bessel filter: the response is a good approximation to a gaussian.
- Satisfies the DECT spectral requirements.

step responses



dashed: ideal gaussian
solid: 8th order Bessel



Comparison

Digital shaping

– With high bit rates, smoothing filter is quite complicated.

– Tuning may be necessary for the smoothing filter.

– Cutoff frequency of the smoothing filter > pulse shaping bandwidth.

\+ At low bit rates, the smoothing filter is simple.

\+ Easily adaptable to I/Q modulators.

Analog shaping

\+ For high data rates, just about as complicated as the smoothing filter in the digital method.

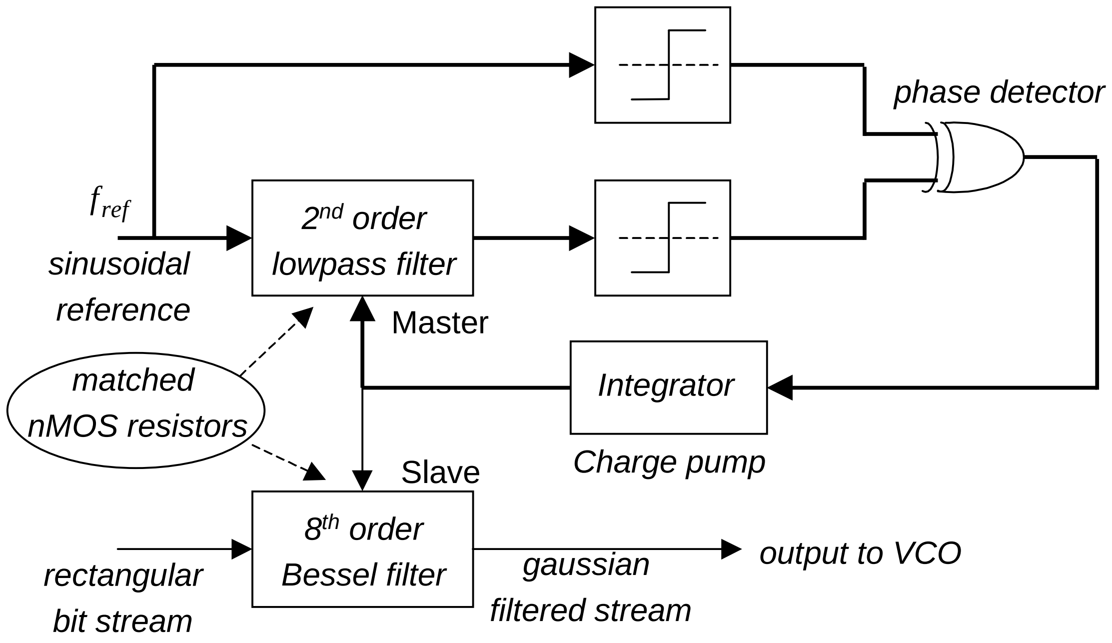
\+ Smaller cutoff frequency than the smoothing filter.

\+ Eliminates the DAC and the ROM → lesser power, area.

– Requires bandwidth tuning.

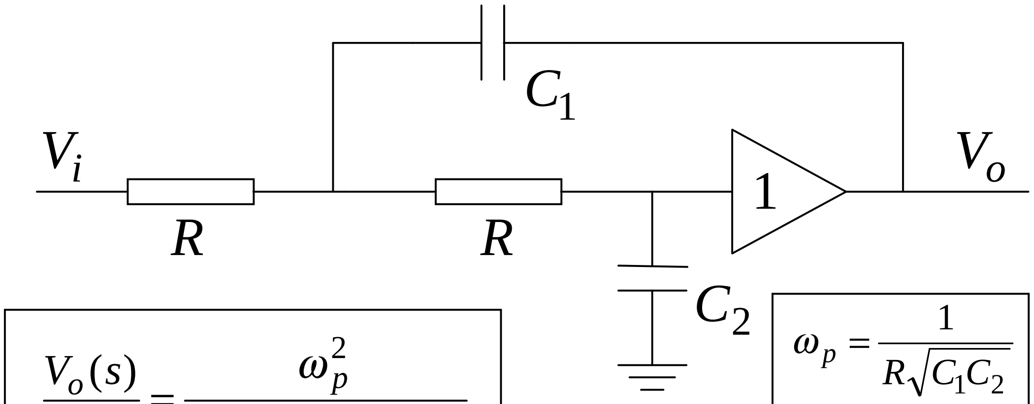
– Only for direct VCO modulation.

Pulse shaping filter with automatic tuning



- Pulse shaping filter:
  - B=576 kHz,$1/T_b$ = 1.152 Mb/s (DECT: $BT_b = 0.5$)
- Master filter tuned to 2 MHz - slave tuned by matching.
- Bessel filter : low Q factors → no Q tuning.
- Slave frequencies, Q factors are determined by reference frequency and capacitor ratios.

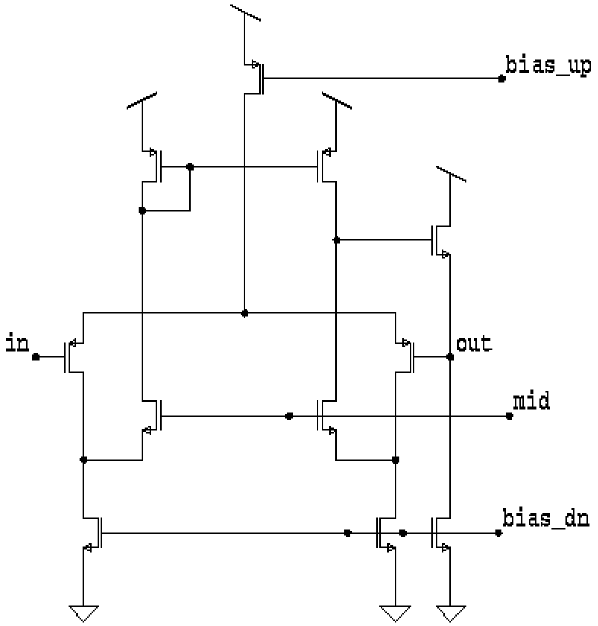
Sallen-Key Biquad



$$\frac{V_o(s)}{V_i(s)} = \frac{\omega_p^2}{s^2 + sQ\omega_p + \omega_p^2}$$

$$\omega_p = \frac{1}{R\sqrt{C_1C_2}}$$

$$Q = \frac{1}{2}\sqrt{\frac{C_1}{C_2}}$$



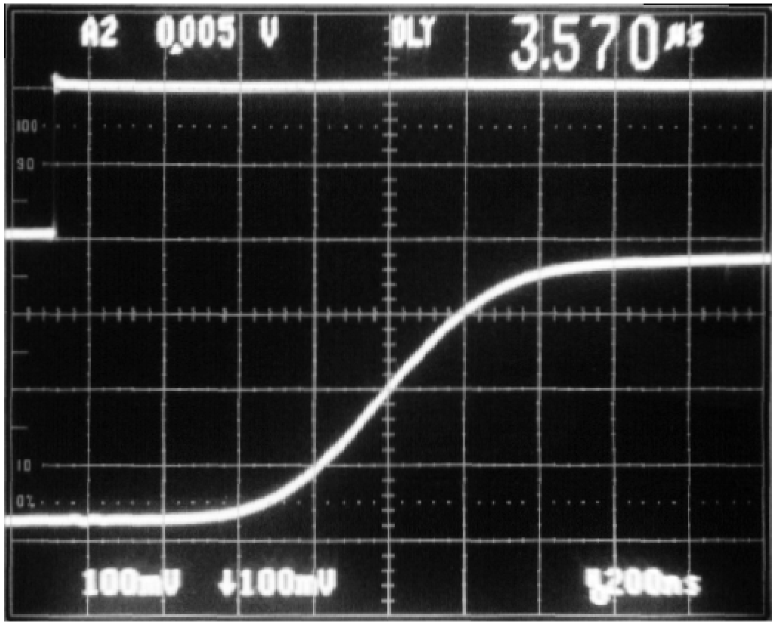
Unity gain buffer

- Low Q values → low sensitivity.
- Simplicity.
- Resistors: nMOS in triode region.
- Pseudo differential structure to eliminate even-order distortion.

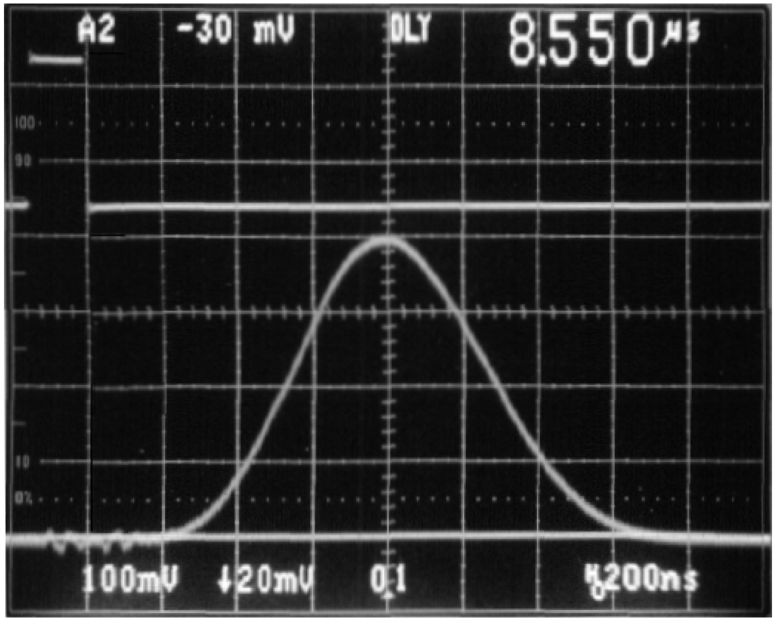
- Cascoded differential pair in unity feedback.
- Quiescent near ground for maximum tunability.

Measured Characteristics

Step response



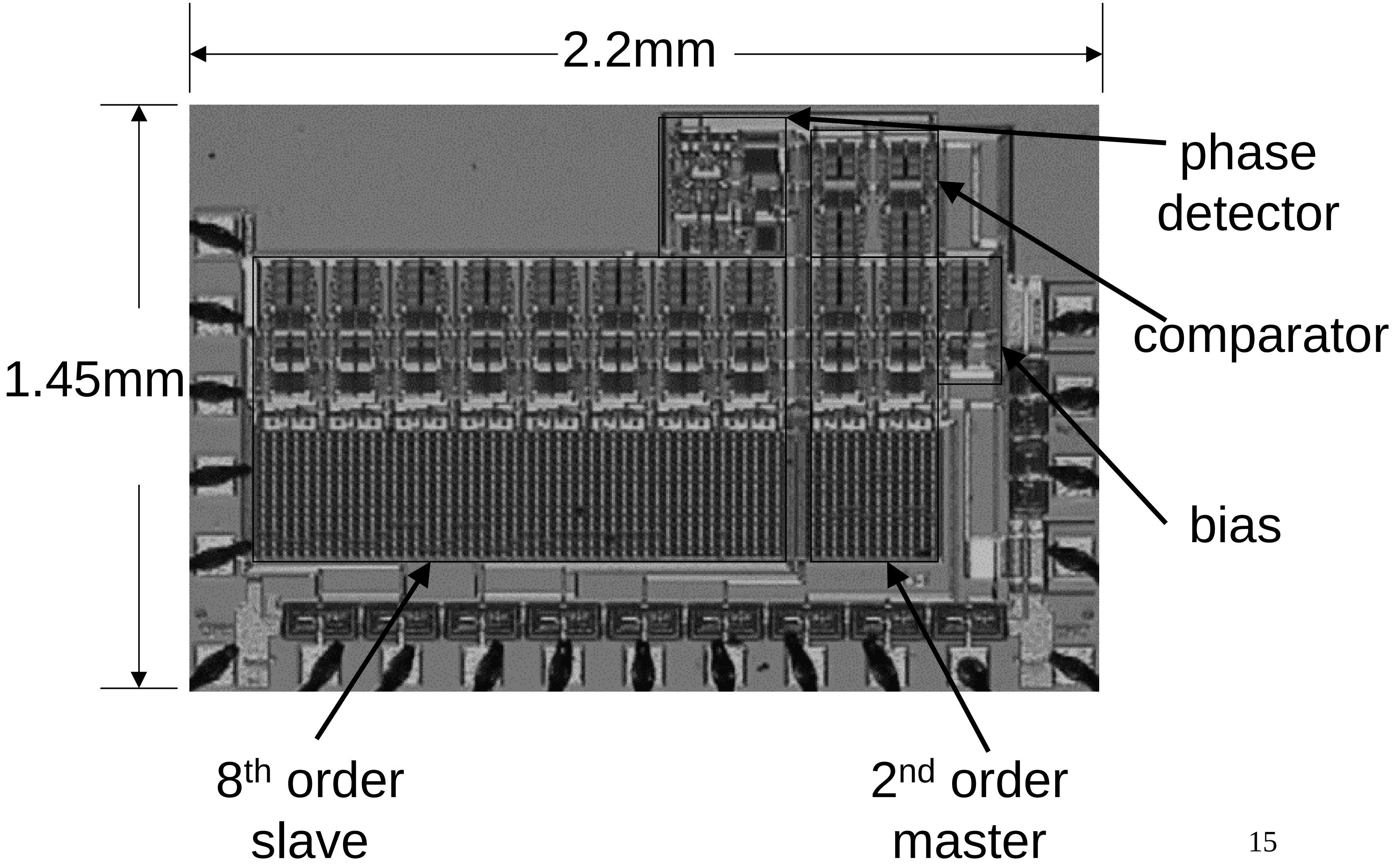
Response to a short pulse



Measured Characteristics

Technology	2µm n-well CMOS
Supply voltage	3.3 V
Chip area (without pads)	2.3 mm^2
Capacitance	73.7 pF
Reference	2 MHz, sinusoidal
Power consumption	9.2 ± 0.24 mW
Dc gain	-0.27 ± 0.05 dB
Dc offset(differential)	15 ± 9.8 mV
f_{-3dB}, nom	577 ± 9.7 kHz
Output noise (50kHz - 5 MHz)	409 ± 5.7 µV
Ref. feedthrough	-70.6 ± 0.32 dB
$V_{ipp,max}$ (THD < 40 dB) [50 kHz tone]	1.63 ± 0.06 V
S / (N+D) when THD=N [50 kHz tone]	52.8 ± 0.38 dB
$V_{ipp,max}$ (THD < 40 dB) [576 kHz tone]	0.56 ± 0.04 V
S / (N+D) when THD=N [576 kHz tone]	46.1 ± 0.48 dB

Chip photograph



Conclusions

- A method for analog gaussian pulse shaping is proposed.
- Power and area savings over the existing method for high bit rates.
- Simulations demonstrate that DECT spectral specifications are satisfied.
- Pulse shaping chip with automatic tuning is fabricated.
- Measurement results are given.