1V Compact Class-AB CMOS Log Filters

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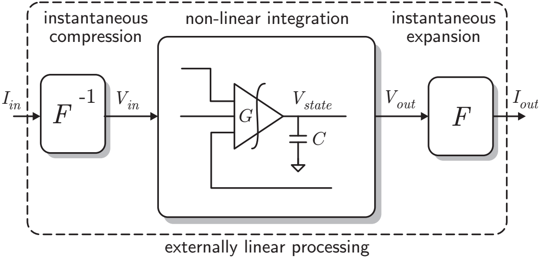
Companding filtering scenario

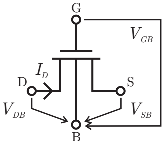


log-domain: $F(x) = e^x$

- ✓ Low-voltage
- ? Low-current vs dynamic range
- ? Low-area vs auxiliary circuitry

. . . the answer is **compact Class-AB**!

MOS log-mapping



weak inversion:

$$V_{SB,DB} \gg \frac{V_{GB} - V_{TO}}{n}$$

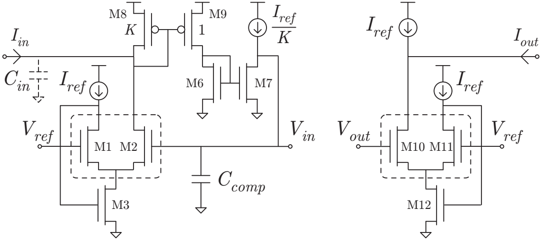
forward saturation:

$$V_{DB} - V_{SB} \gg U_t$$

$$I_D = I_S e^{\frac{V_{GB} - V_{TO}}{nU_t}} e^{-\frac{V_{SB}}{U_t}}$$

$$I_S = 2n\beta U_t^2 \qquad IC = \frac{I_D}{I_S}$$

Compressor and expander



boxed devices in weak inversion saturation:

$$I = F(V) = I_{ref} e^{\frac{V - V_{ref}}{nU_t}} \qquad I > 0$$

Note: presented by same authors in ISCAS'00

- ✓ V_{ref} used to optimize low-voltage: M3,12 do not need saturation!
- ✓ K allows simple frequency compensation

$$\zeta = \frac{1}{2}\sqrt{\frac{KC_{comp}}{C_{in}}}$$
$$K \geq 2\frac{C_{in}}{C_{comp}}$$

- × I_{ref} limits the full-scale due to log-mapping:

$$I_{max} \equiv \frac{I_{ref}}{2}$$

with thermal noise:

$$\Delta SNR = +3\text{dB}/oct(I_{ref})$$

. . . **poor** improvement!

Integrator

- ODE in the lineal I-domain:

$$\frac{\mathrm{d}I_{out}}{\mathrm{d}t} = \pm\frac{1}{\tau}I_{in}$$

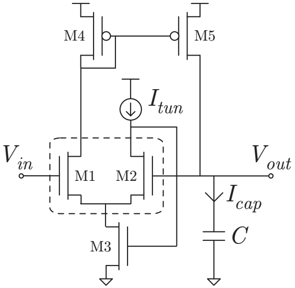
- ODE in the compressed V-domain:

$$\frac{\mathrm{d}V_{out}}{\mathrm{d}t} = \pm\frac{nU_t}{\tau}e^{\frac{V_{in}-V_{out}}{nU_t}}$$

- ODE in the circuit Q-domain:

$$\frac{\mathrm{d}Q_{out}}{\mathrm{d}t} = \underbrace{C\frac{\mathrm{d}V_{out}}{\mathrm{d}t}}_{I_{cap}} = \pm I_{tun}e^{\frac{V_{in}-V_{out}}{nU_t}}$$

$$\tau = \frac{nU_tC}{I_{tun}}$$



- ✓ Tunable time constant
- ✓ Single dis/charge due to log mapping ($I_{in} > 0$), op ensured at filter level
- ✓ Half integrator shared
- × SNR issues ($I_{tun} \geq I_{ref}$) cause **high-value** C!

Input Splitter and Compressor

- Differential signaling:

$$I_{in} = I_{inp} - I_{inn}$$
$$I_{inp,n} > 0$$

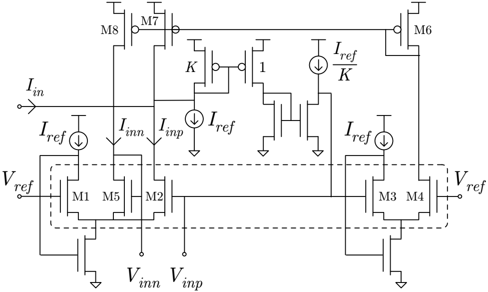
- Constant geometric mean splitting:

$$I_{inp} I_{inn} = I_{ref}^2$$

✓ Same low-voltage capability as Class-A

✓ Full-scale $I_{max} \leftrightarrow I_{ref}$

✓ **Optimization**: $I_{ref} \downarrow$ $\Delta SNR \simeq$ +6dB$/oct(I_{max})$



- current multiplier M1-M4
- $\frac{I_{ref}^2}{I_{inp}}$ feedback M6-M8
- M2 shared by TL+compressors

Differential Integrator with CMFB (1)

- ODE in the linear I-domain for multiple-inputs:

$$\frac{dI_{out}}{dt} = \frac{1}{\tau} \sum_K \pm I_{inK} \quad \text{(even different } \tau_K\text{)}$$

- High-gain **CMFB** to ensure geometric-mean common-mode:

$$\frac{dI_{outp}}{dt} = \frac{1}{\tau}\left[\sum_K \pm I_{inpK} - \frac{I_{outp}I_{outn}}{I_{ref}} + I_{ref}\right]$$

$$\frac{dI_{outn}}{dt} = \frac{1}{\tau}\left[\sum_K \pm I_{innK} - \frac{I_{outp}I_{outn}}{I_{ref}} + I_{ref}\right]$$

✓ Does not affect I_{out}

✓ CMFB **overhead**
$\propto$ filter order
$\not\leftrightarrow$ filter complexity

Differential Integrator with CMFB (2)

- ODE in the compressed V-domain:

$$\frac{dV_{outp}}{dt} = \frac{nU_t}{\tau}\left[\sum_K \pm\frac{I_{inpK}}{I_{outp}} - \frac{I_{outn}}{I_{ref}} + \frac{I_{ref}}{I_{outp}}\right]$$

$$\frac{dV_{outn}}{dt} = \frac{nU_t}{\tau}\left[\sum_K \pm\frac{I_{innK}}{I_{outn}} - \frac{I_{outp}}{I_{ref}} + \frac{I_{ref}}{I_{outn}}\right]$$

- Finally, ODE in the circuit Q-domain:

$$\frac{dQ_{outp}}{dt} = I_{tun}\left[\sum_K \pm e^{\frac{V_{inpK}-V_{outp}}{nUt}} - e^{\frac{V_{outn}-V_{ref}}{nUt}} + e^{\frac{V_{ref}-V_{outp}}{nUt}}\right]$$

cross ↕ coupled

$$\frac{dQ_{outn}}{dt} = I_{tun}\left[\sum_K \pm e^{\frac{V_{innK}-V_{outn}}{nUt}} - e^{\frac{V_{outp}-V_{ref}}{nUt}} + e^{\frac{V_{ref}-V_{outn}}{nUt}}\right]$$

Differential Integrator with CMFB (and 3)

- Realization:

$$\frac{dQ_{outp}}{dt} = I_{tun}\left[\sum_K \pm e^{\frac{V_{inpK}-V_{outp}}{nUt}} - e^{\frac{V_{outn}-V_{ref}}{nUt}} + e^{\frac{V_{ref}-V_{outp}}{nUt}}\right]$$

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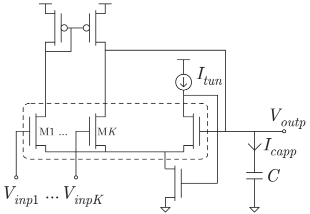

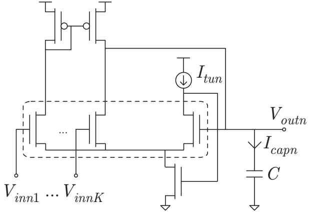

- ✓ Low-voltage capability
- ✓ Most CMFB shared by $1 \ldots K$
- ✓ Half CMFB shared by all C's
- ✓ $I_{ref} \downarrow$ allows $I_{tun} \downarrow$, so **downscaling** C (Si area)

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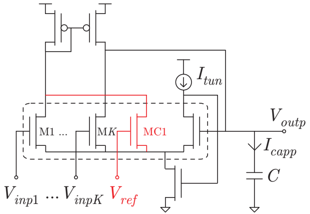

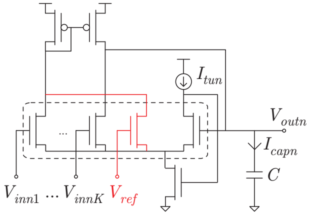

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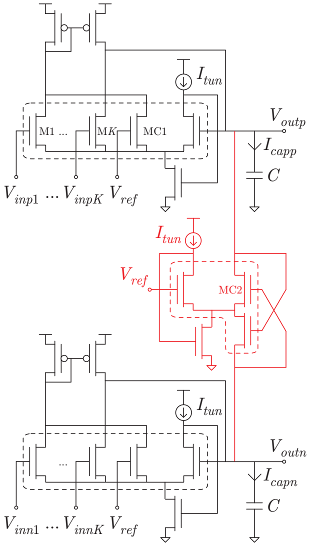

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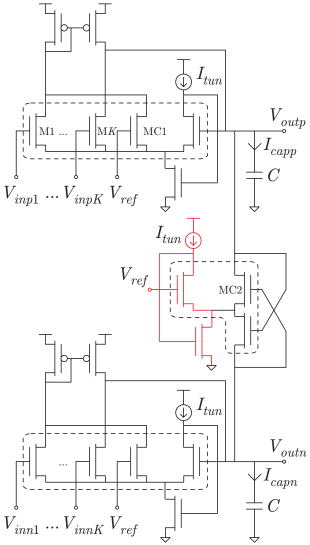
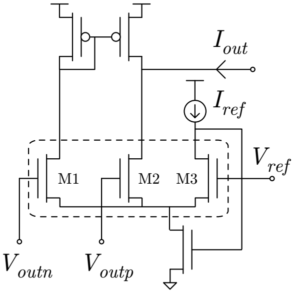


Output Expanders



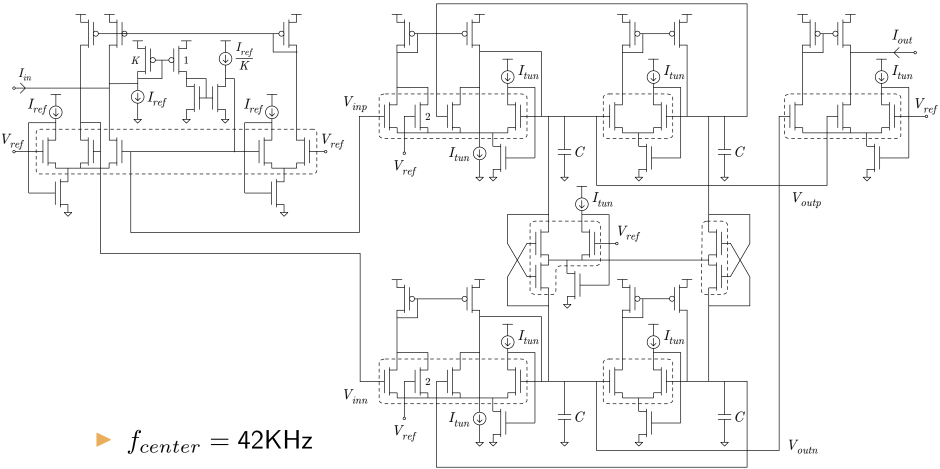
- Differential to single-ended:

$$I_{out} = I_{outp} - I_{outn}$$

$$I_{out} = I_{ref}\left[e^{\frac{V_{outp}-V_{ref}}{nU_t}} - e^{\frac{V_{outn}-V_{ref}}{nU_t}}\right]$$

- ✓ Low-voltage capability like Class-A
- ✓ Same $I_{ref}\downarrow$ as compressors
- ✓ M1,2 expanders share half circuitry
- ✓ For multiple outputs, all expanders can **share** this part...

Second-Order Band-Pass Log-Filter

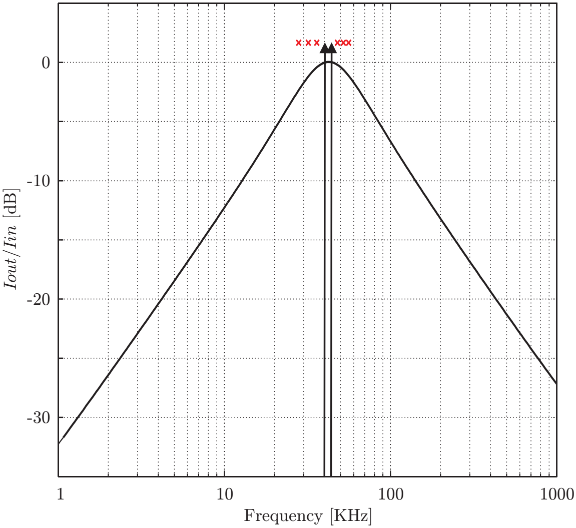


- $f_{center} = 42\text{KHz}$
- $Q = 1$

Class-A versus New Class-AB

- 0.35μm CMOS technology
- Designed for the **same full-scale**
- IMD analysis through periodic steady-state (PSS) simulations:

f_{in1} = 40KHz
f_{in2} = 44KHz



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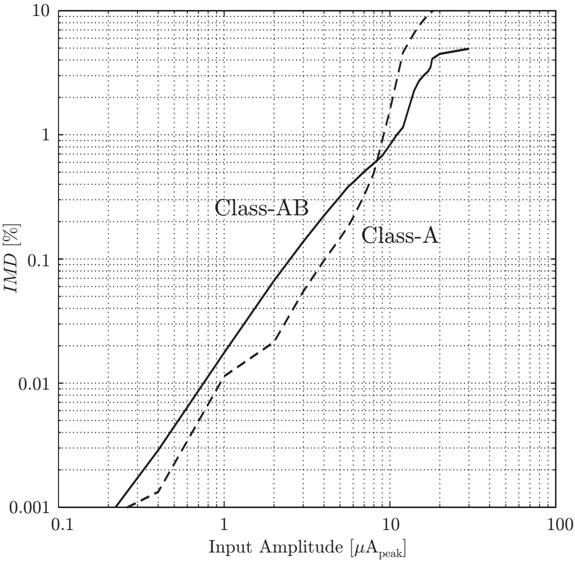

Overall Results

	Class-A	Class-AB	Units
Supply voltage	1		V
$V_{TON}+\|V_{TOP}\|$	1.2		V
V_{ref}	0.5		V
I_{ref} (and I_{tun})	10	**2.5**	μA
C	1000	**250**	pF
Boxed-MOSFET ratios	$50\times\frac{40}{1.5}$	$21\times\frac{40}{1.5}$	$\frac{\mu m}{\mu m}$
Signal full-scale	$\sim$10		μA_p
IMD @ half full-scale	0.15	0.3	%
DR (10KHz-100KHz)	68	>68	dB
Quiescent power	150	**85**	μW
Total capacitance	2000	**1000**	pF
Total boxed-MOS area	0.033	0.037	mm^2

✓ -40% overall power ✓ -50% capacitance area

Conclusions

- Very **low-voltage Class-AB** CMOS log filters
- **Complete** set of basic building blocks:
  splitting, compression, expansion, integration and CMFB
- Quiescent **low-power** consumption
- **Compact** area with reduced circuit overhead
- 0.35μm CMOS Class-A/AB comparative **example**