ANALOG CIRCUITS DESIGN

AE7: Power stages at low frequencies

Course overview

- 1. Introduction
- 2. The bipolar transistor
- 3. Push-pull stage
- 4. Classes of operation
- 5. Class D amplifier
- 6. Heatsink calculation

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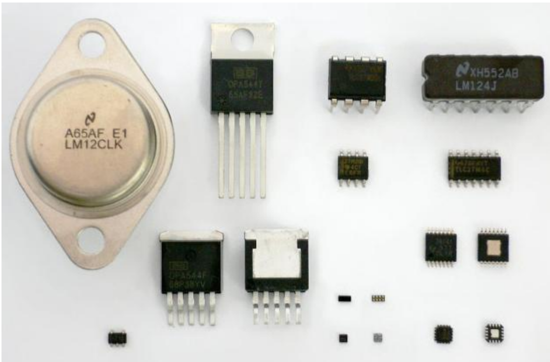
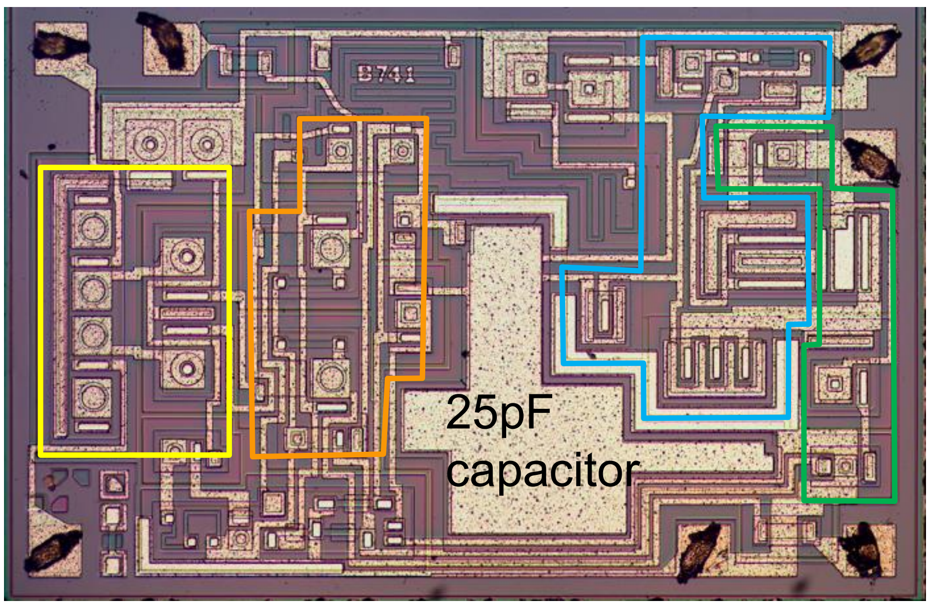
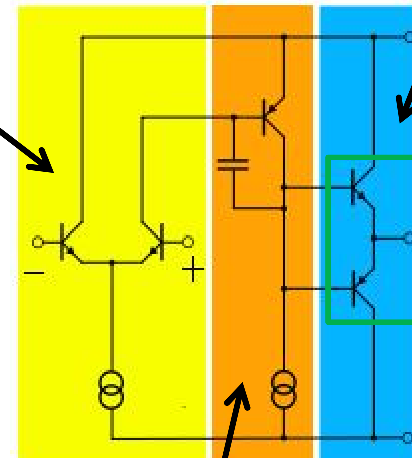
1. Introduction: inside the 741 operational amplifier

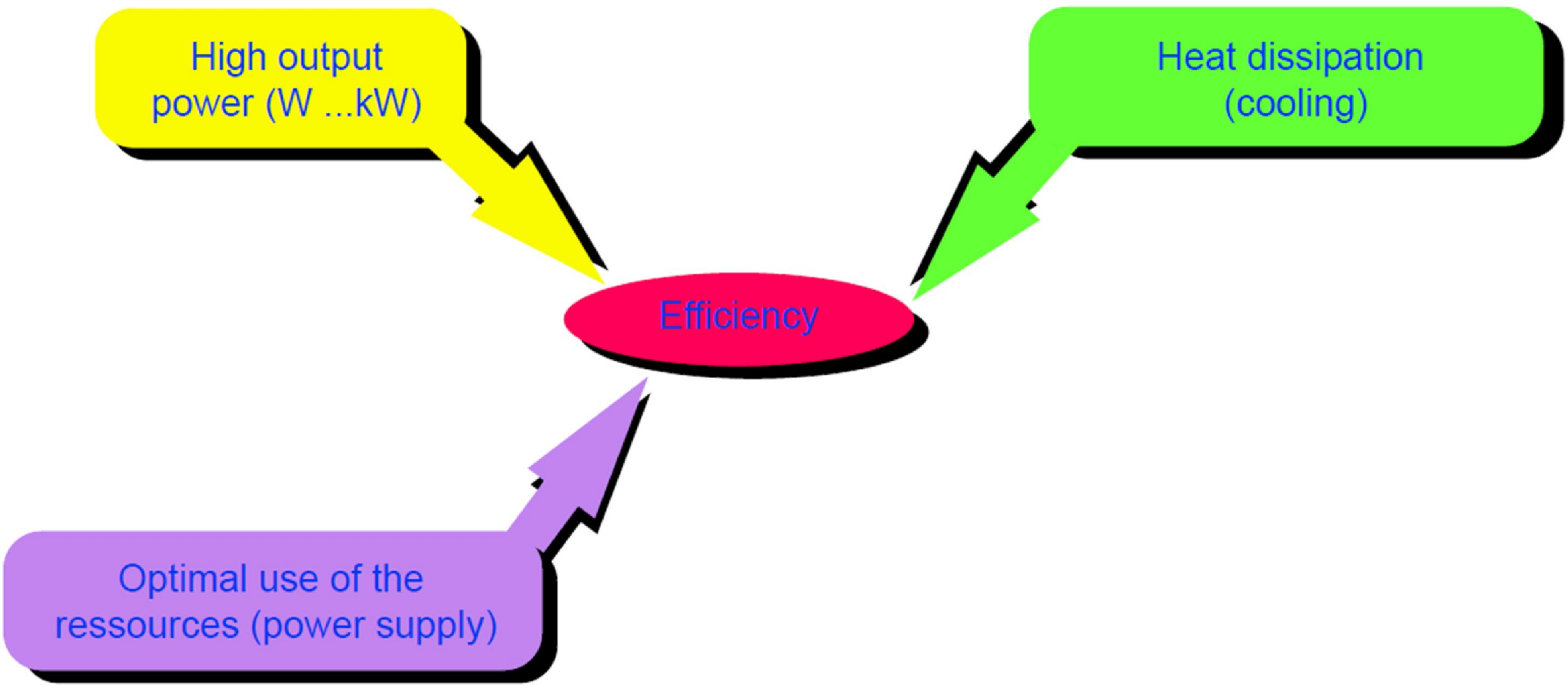




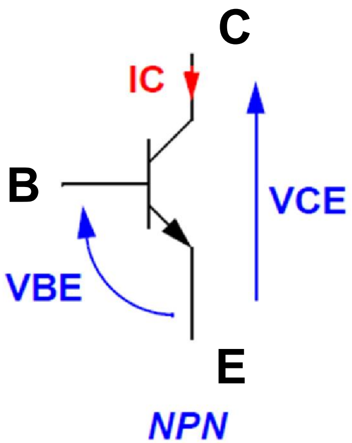


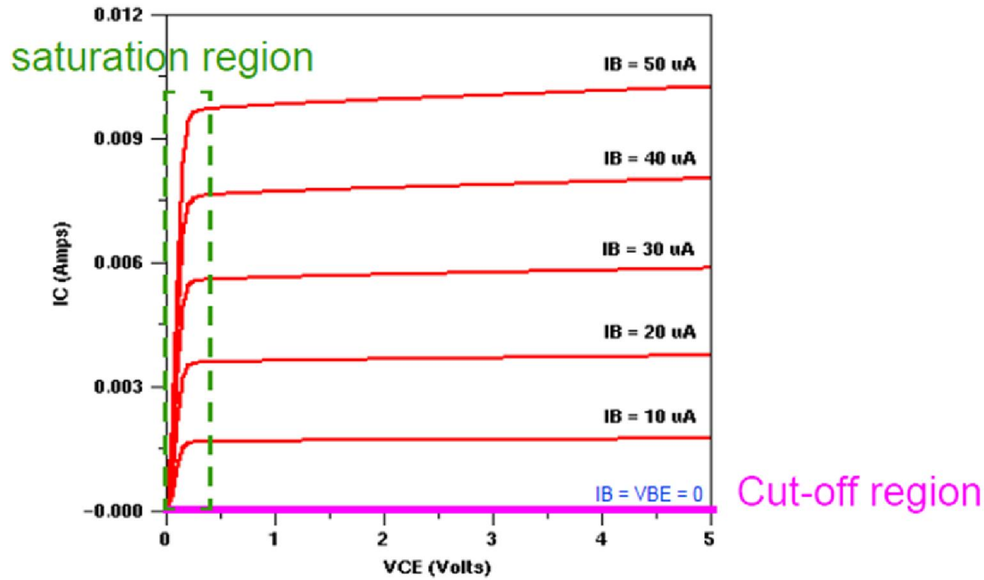
Source: http://www.righto.com/2015/10/inside-ubiquitous-741-op-amp-circuits.html

1. Introduction: system overview



2. The bipolar transistor



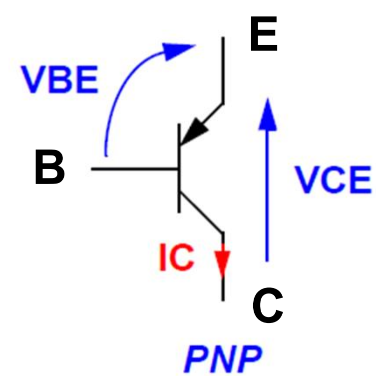


Current source (IC) controlled by a voltage (VBE) provided VCE > 300~400mV

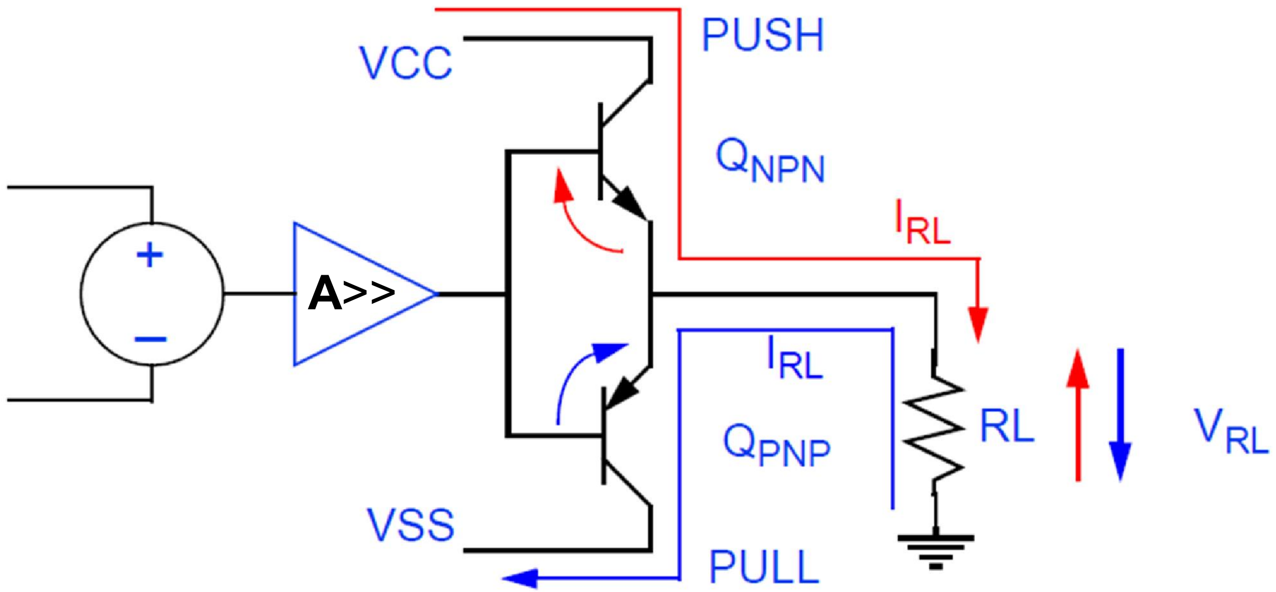
$$IC = Is\left(\exp\left(\frac{VBE}{Vt}\right) - 1\right)$$

$$VBE \approx Vt \ \ln\left(\frac{IC}{IS}\right) \approx 0,6V$$

PNP & NPN: same behaviour, but voltages and currents are in the opposite direction

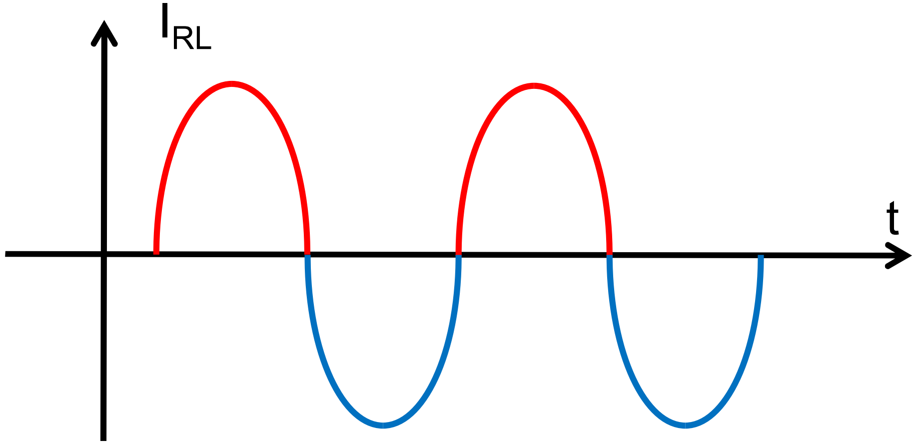


3. Push-pull output stage: operation



Q_{NPN} and Q_{PNP} are complementary transistors

Zero bias (quiescent) current



3. Push-pull output stage: efficiency

Assumption: symetric supply VCC = |VSS|

- Power delivered to the load:

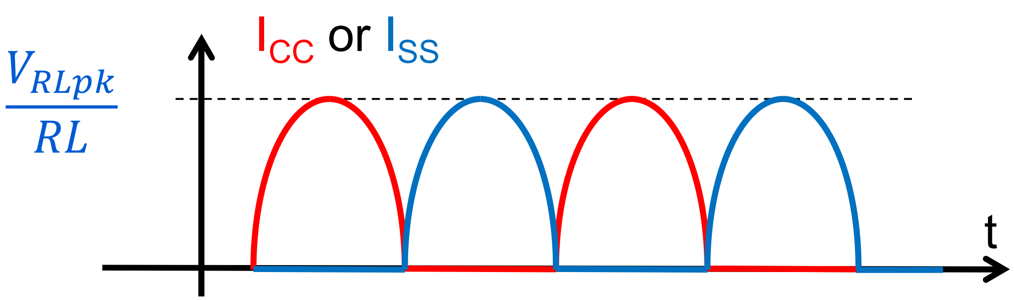
$$P_{RL} = \frac{(V_{RLpk})^2}{2 \cdot RL}$$

- Efficiency

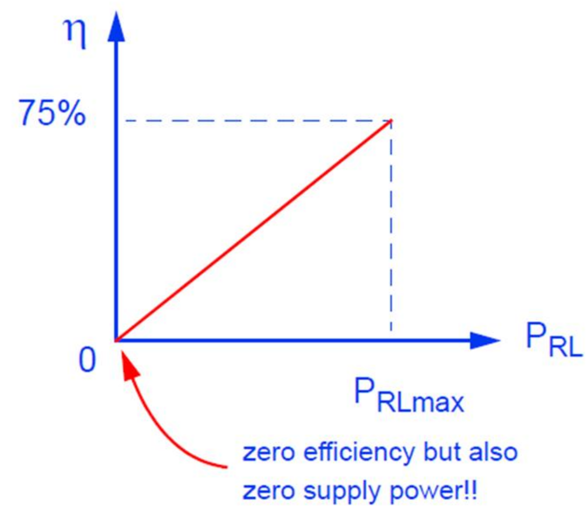
$$\eta = \frac{P_{RL}}{P_{supply}} = \frac{\pi \cdot V_{RLpk}}{4 \cdot VCC}$$

- $P_{supply} = P_{VCC} + P_{VSS}$

$$P_{supply} = VCC\ ICCavg + VSS\ ISSavg$$



$$P_{supply} = 2\,VCC\,\frac{V_{RLpk}}{\pi\,RL}$$



3. Push-pull output stage: power losses

General methodology: $\Sigma P_{supply} = P_{RL} + P_{transistor(s)} + \varepsilon$

power stage only

the rest of the circuit (may usually be neglected)

Power dissipated when the input signal is a sine wave (for 2 transistors):

$$P_{diss} = \frac{2 \cdot VCC \cdot V_{RLpk}}{\pi \cdot RL} - \frac{V_{RLpk}^{2}}{2 \cdot RL}$$

reaches maximum at $V_{RLpk} = \frac{2 \cdot VCC}{\pi}$

$$P_{diss(max)} = \frac{2 \cdot VCC^2}{\pi^2 \cdot RL}$$

$\approx$ 40% of maximum P_{RL}

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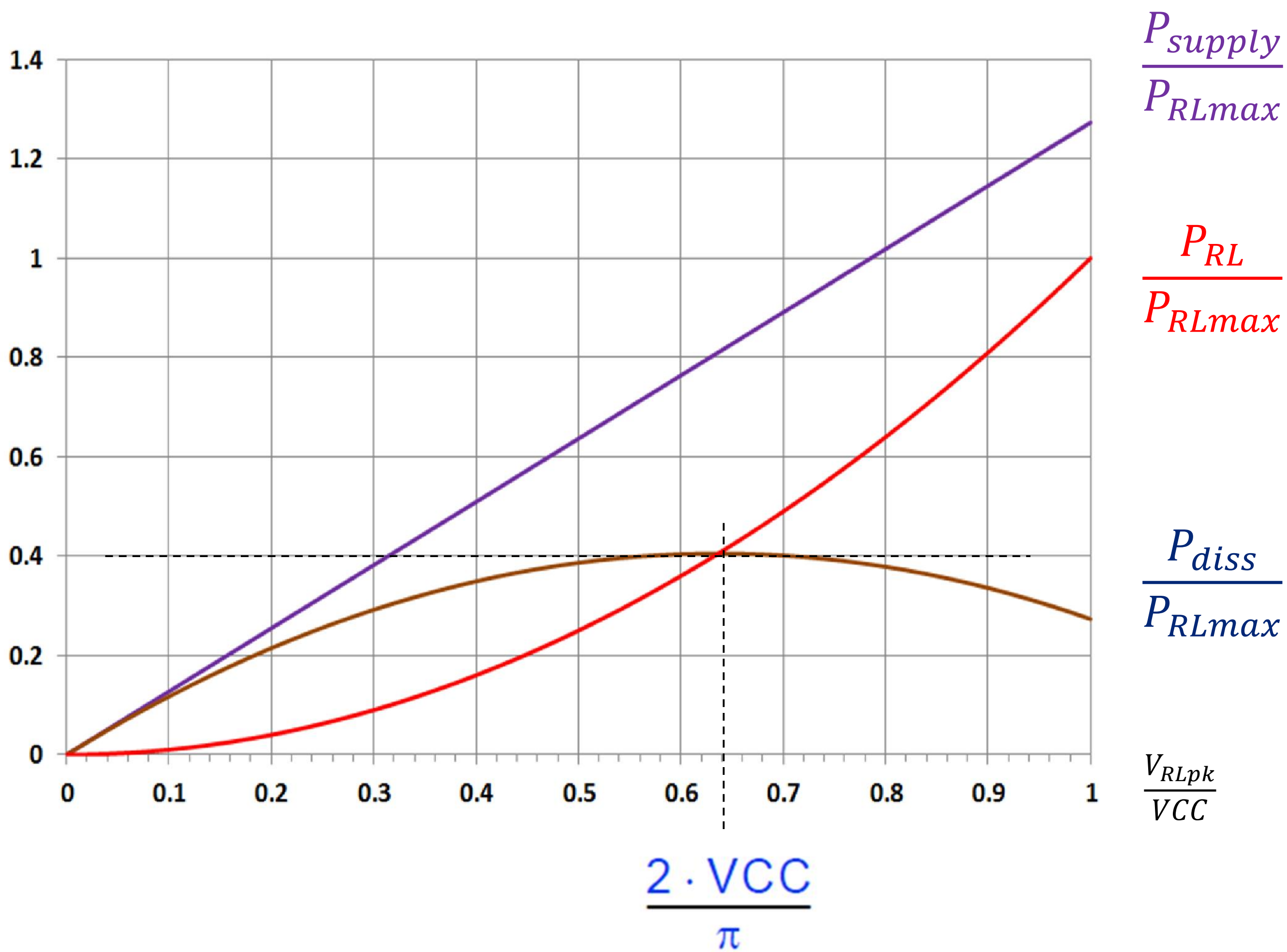
3. Push-pull output stage: power losses

$$P_{diss(max)} = \frac{2 \cdot VCC^2}{\pi^2 \cdot RL}$$

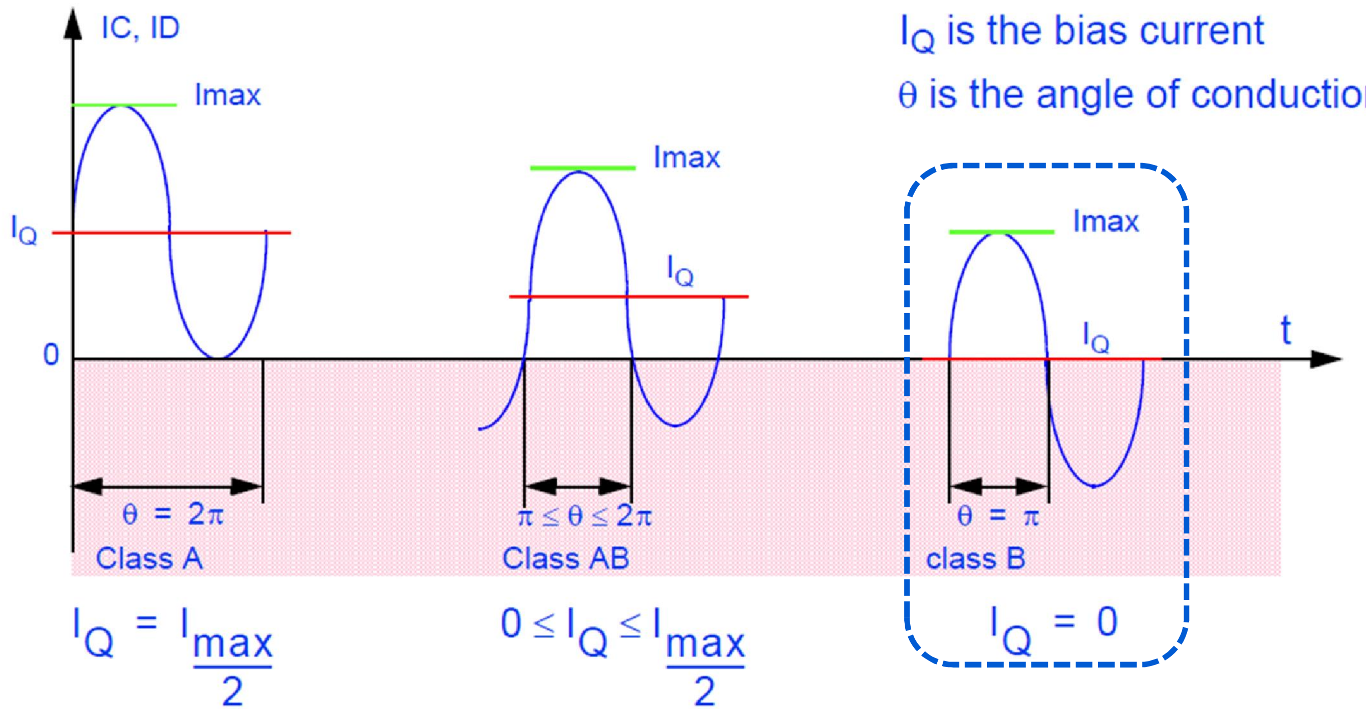
$\approx$ 40% of maximum P_{RL}



4. Class of operation

I_Q is the bias current

θ is the angle of conduction



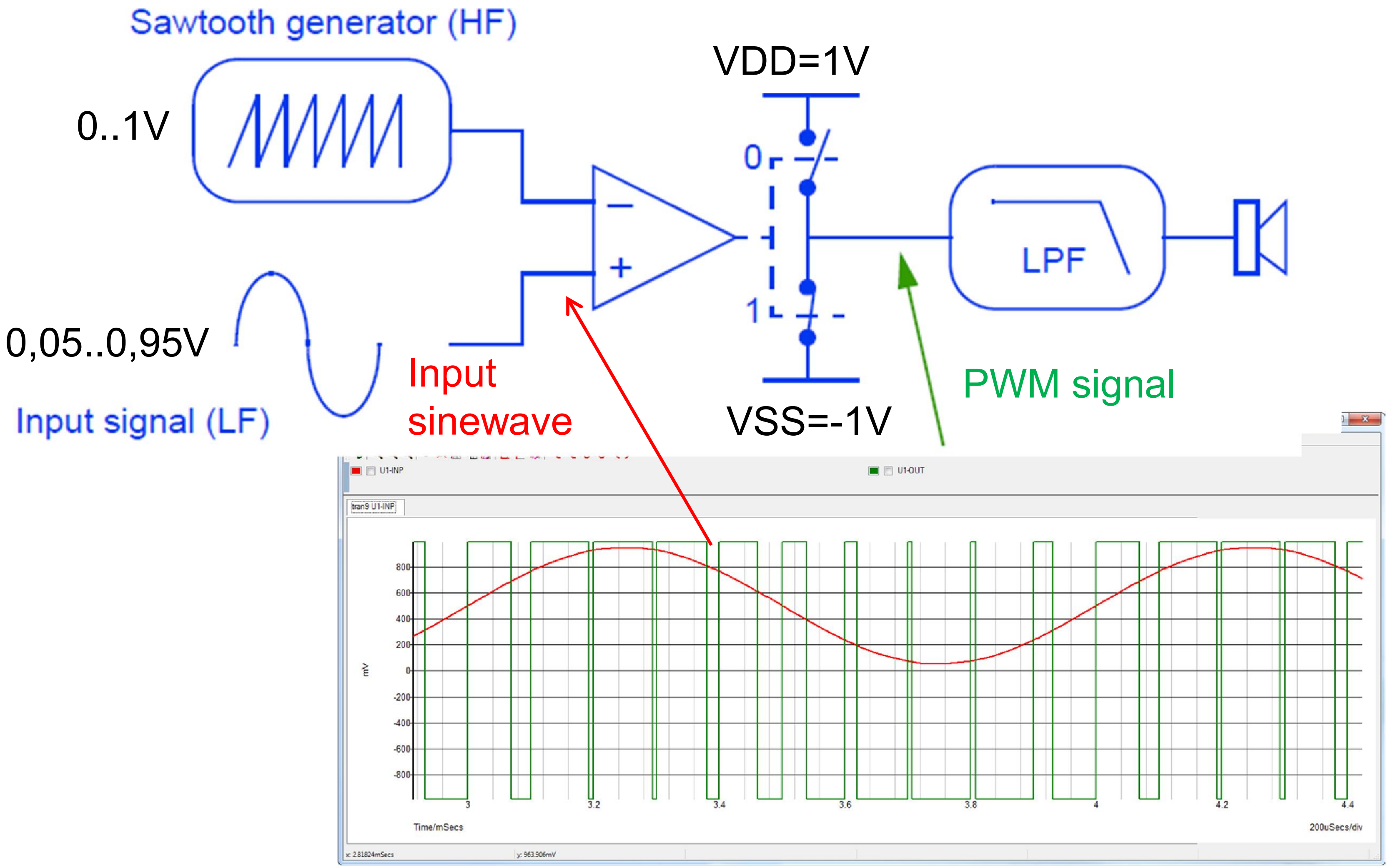
Efficiency = 25%

Push-pull
Efficiency = 75%

Class A, AB, B ➡ limited or bad efficiency due to simultaneous presence of voltage and current on the active device

Class D ➡ switching operation cancels losses in active devices

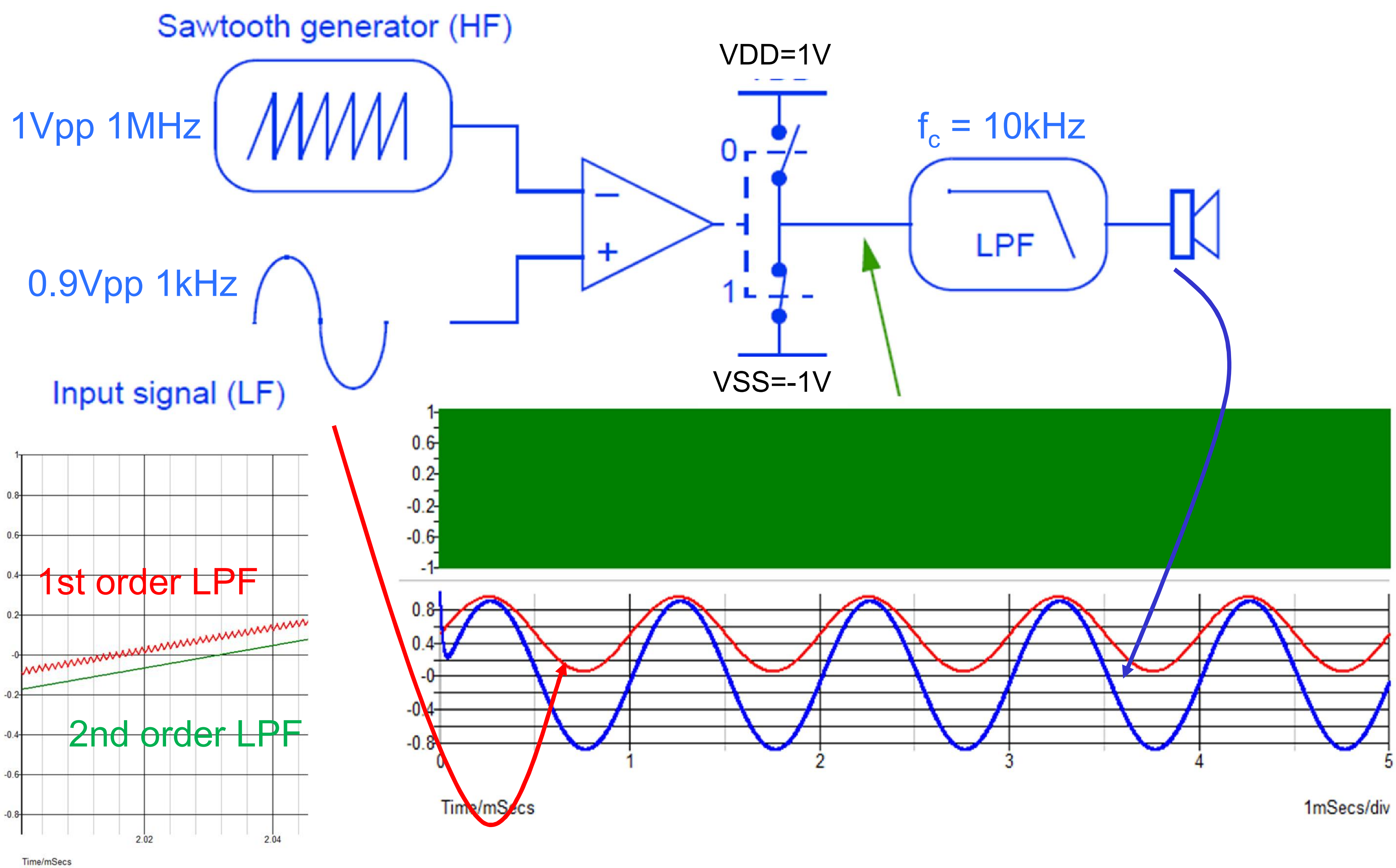
5. Class-D amplifiers: operation



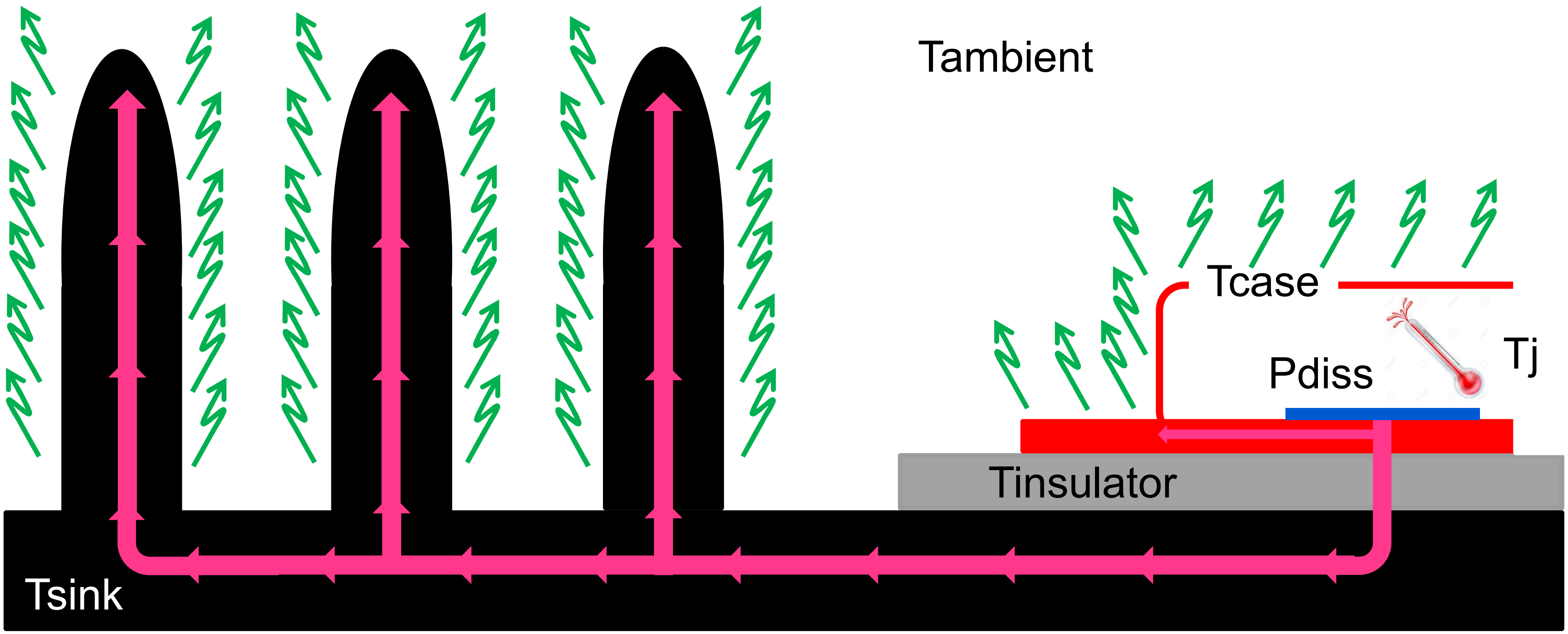
switch open: non-zero voltage, zero current
switch closed: non-zero current, zero voltage

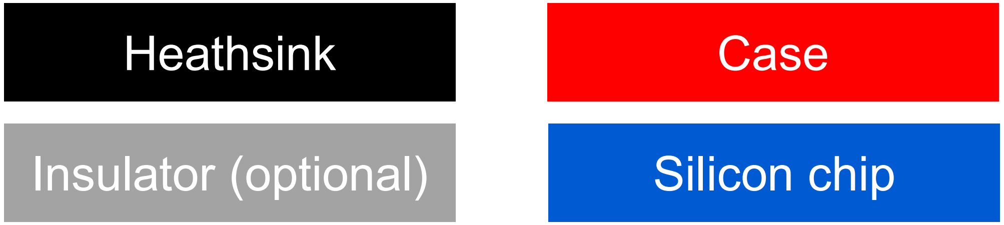
no dissipated power, 100% efficiency

5. Class-D amplifiers: more realistic example



6. Heathsink calculation: thermal model





6. Heathsink calculation: thermal-electrical model

Power ⟷ Current

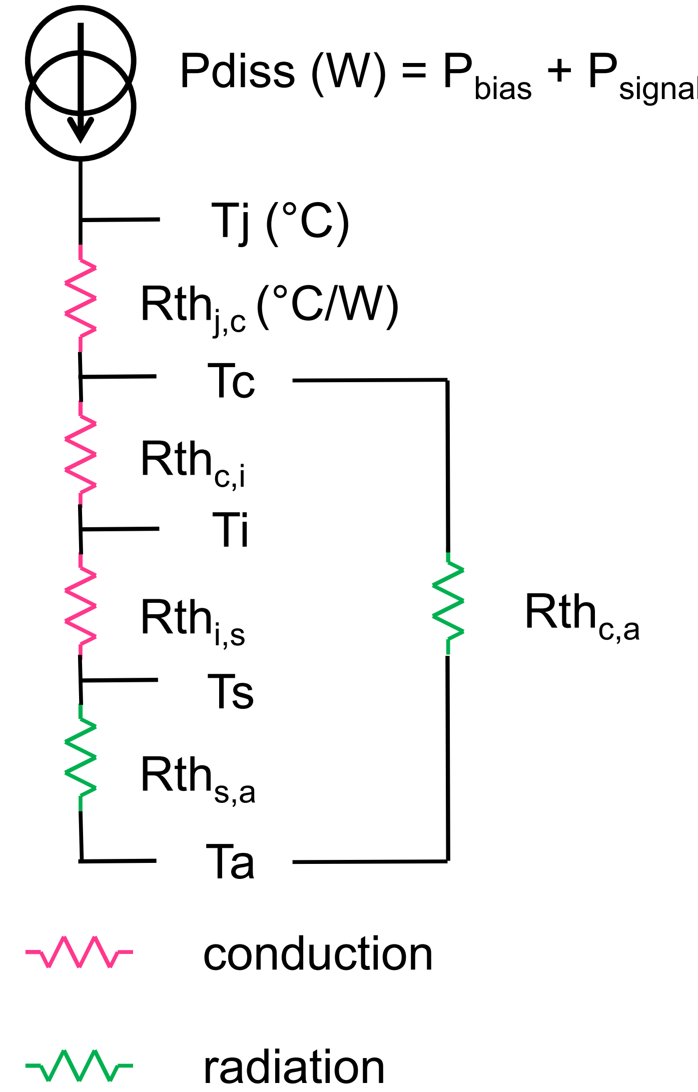
Temperature ⟷ Voltage

Thermal resistance ⟷ Resistance

$$T_j - T_a = P_{diss} \sum Rth$$

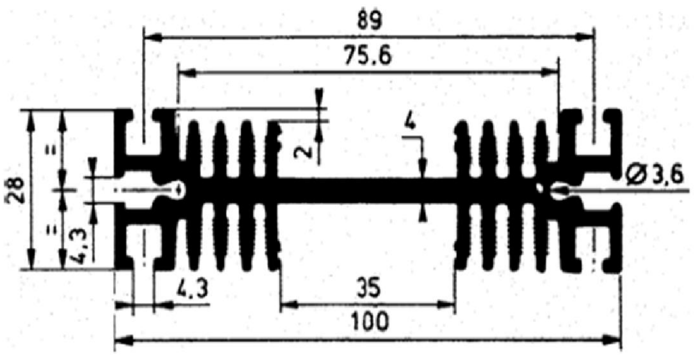
$$Rth_{s,a} = \frac{T_j - T_a}{P_{diss}} - Rth_{j,c} - Rth_{c,i} - Rth_{i,s}$$

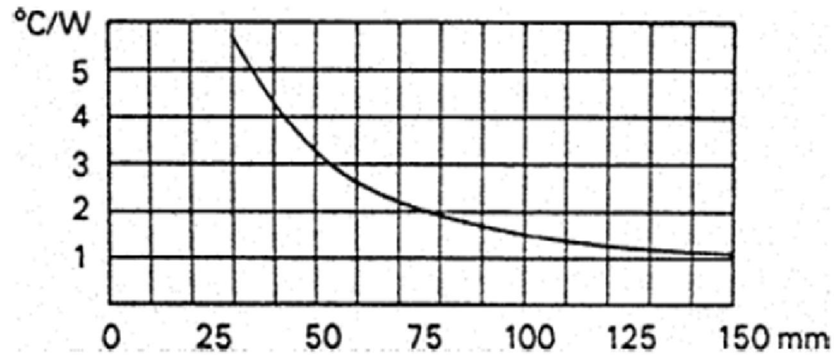
($Rth_{c,a}$ neglected)



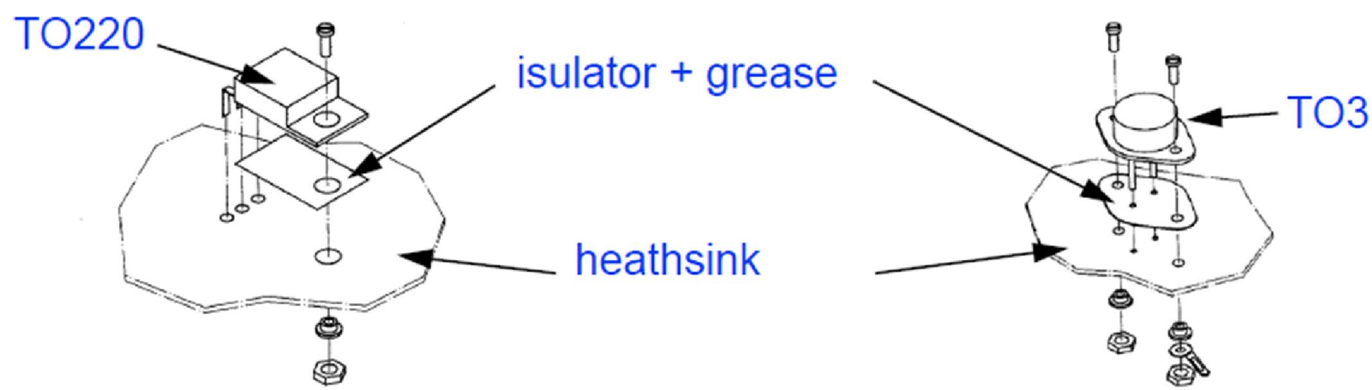
6. Heathsink calculation: mechanical considerations

- Thermal resistance depends on profile type and dimension:





- Mounting a transistor on the heatsink:



6. Heathsink calculation: voltage regulator example

Figure 4. Application circuits

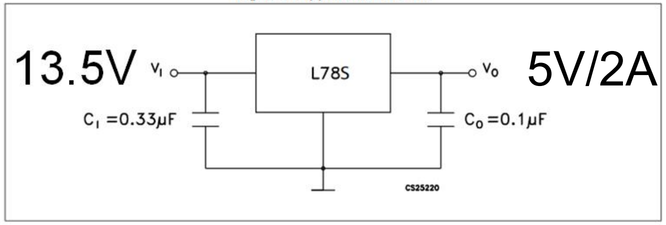


Table 2. Absolute maximum ratings

Symbol	Parameter		Value	Unit
V_I	DC input voltage	for V_O= 5 to 18V	35	V
		for V_O= 24V	40	
I_O	Output current		Internally limited	
P_D	Power dissipation		Internally limited	
T_{STG}	Storage temperature range		-65 to 150	°C
T_{OP}	Operating junction temperature range		0 to 150	°C

Table 3. Thermal data

Symbol	Parameter	TO-220	Unit
R_{thJC}	Thermal resistance junction-case	5	°C/W
R_{thJA}	Thermal resistance junction-ambient	50	°C/W

Ambient temperature: Ta = 30°c

$P_{diss\ max}$ = (13.5 – 5) x 2 = 17W

Without heathsink: $T_j = Pdiss \times Rth_{j,a} + Ta = \mathbf{880°C}$!!!!

Heathsink calculation:
(no insulator)

$$T_j - T_a = P_{diss}\,(Rth_{j,c} + Rth_{c,s} + Rth_{s,a})$$

Hint: limit Tj to 120°C, $Rth_{c,s}$ = 0.2°C/W (thermoconductive grease)

∑ Rth = 5.3°C/W → no practical solution since that yields $Rth_{s,a}$ = 0.1°C/W

6. Heathsink calculation: voltage regulator example

41.6 x 25 x 63.5mm
3°C/W

$\sum Rth = 8.2°C/W \rightarrow Pdiss_{max} = 11W$

→ reduce current downto ≈1.3A max
→ reduce input voltage downto 10.5V
→ use another regulator (TO3 case)

6. Heathsink calculation: audio amplifier example

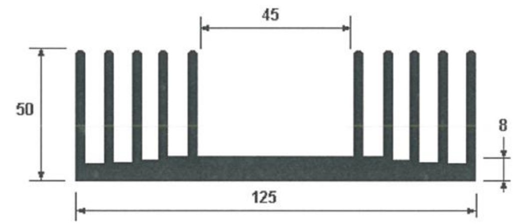
TDA7294 100W class-AB audio amplifier   Pout = 100W → Pdiss $_{max}$ = 40W

THERMAL DATA

Symbol	Description		Value	Unit
$R_{th\ j\text{-}case}$	Thermal Resistance Junction-case	Max	1.5	°C/W

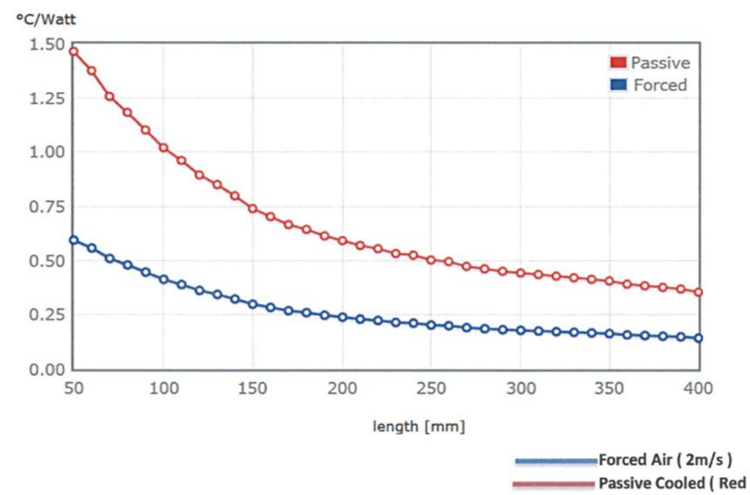
Heathsink calculation:
(no insulator)

$$T_j - T_a = P_{diss}\,(Rth_{j,c} + Rth_{c,s} + Rth_{s,a})$$



Hint: limit Tj to 120°C,
$Rth_{c,s}$ = 0.2°C/W (thermoconductive grease)

∑ Rth = 2.25°C/W → $Rth_{s,a}$ = 0.55°C/W



Forced air: ≈70mm
Passive: ≈250mm

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