ON Semiconductor®

The TL431 in the Control of Switching Power Supplies

Agenda

- ❑ Feedback generalities
- ❑ The TL431 in a compensator
- ❑ Small-signal analysis of the return chain
- ❑ A type 1 implementation with the TL431
- ❑ A type 2 implementation with the TL431
- ❑ A type 3 implementation with the TL431
- ❑ Design examples
- ❑ Conclusion

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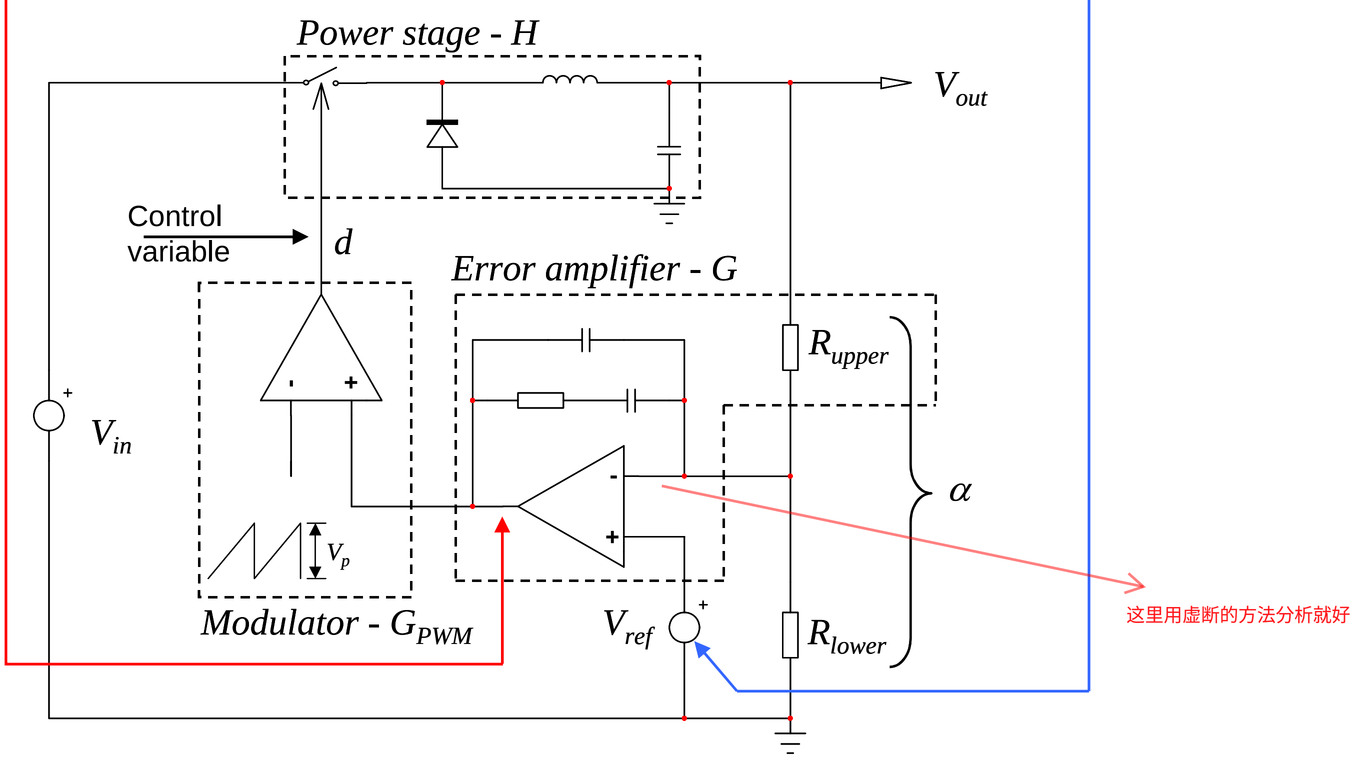
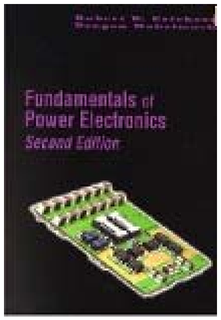
What is a Regulated Power Supply?

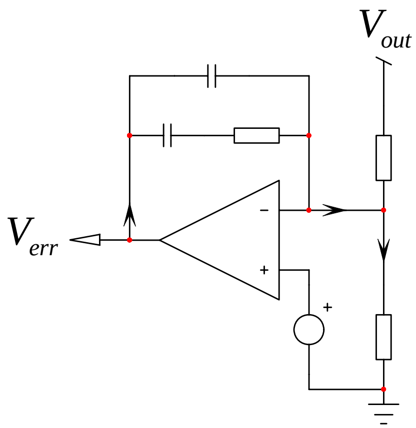
- ❑ V_{out} is permanently compared to a reference voltage $\boxed{V_{ref}}$.
- ❑ The reference voltage V_{ref} is precise and stable over temperature.
- ❑ The error, $\boxed{\varepsilon = V_{ref} - \alpha V_{out}}$, is amplified and sent to the control input.
- ❑ The power stage reacts to reduce ε as much as it can.

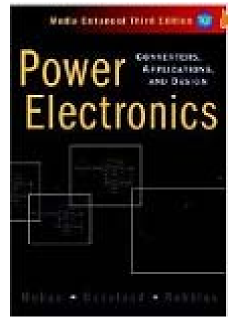


How is Regulation Performed?

- ❑ Text books only describe op amps in compensators…



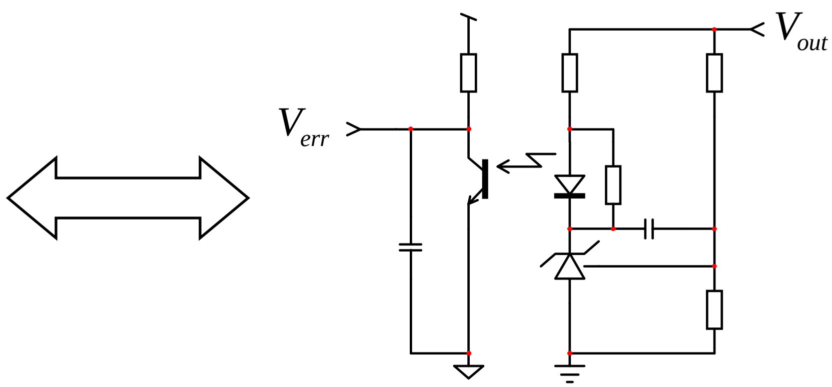




- ❑ The market reality is different: the TL431 rules!

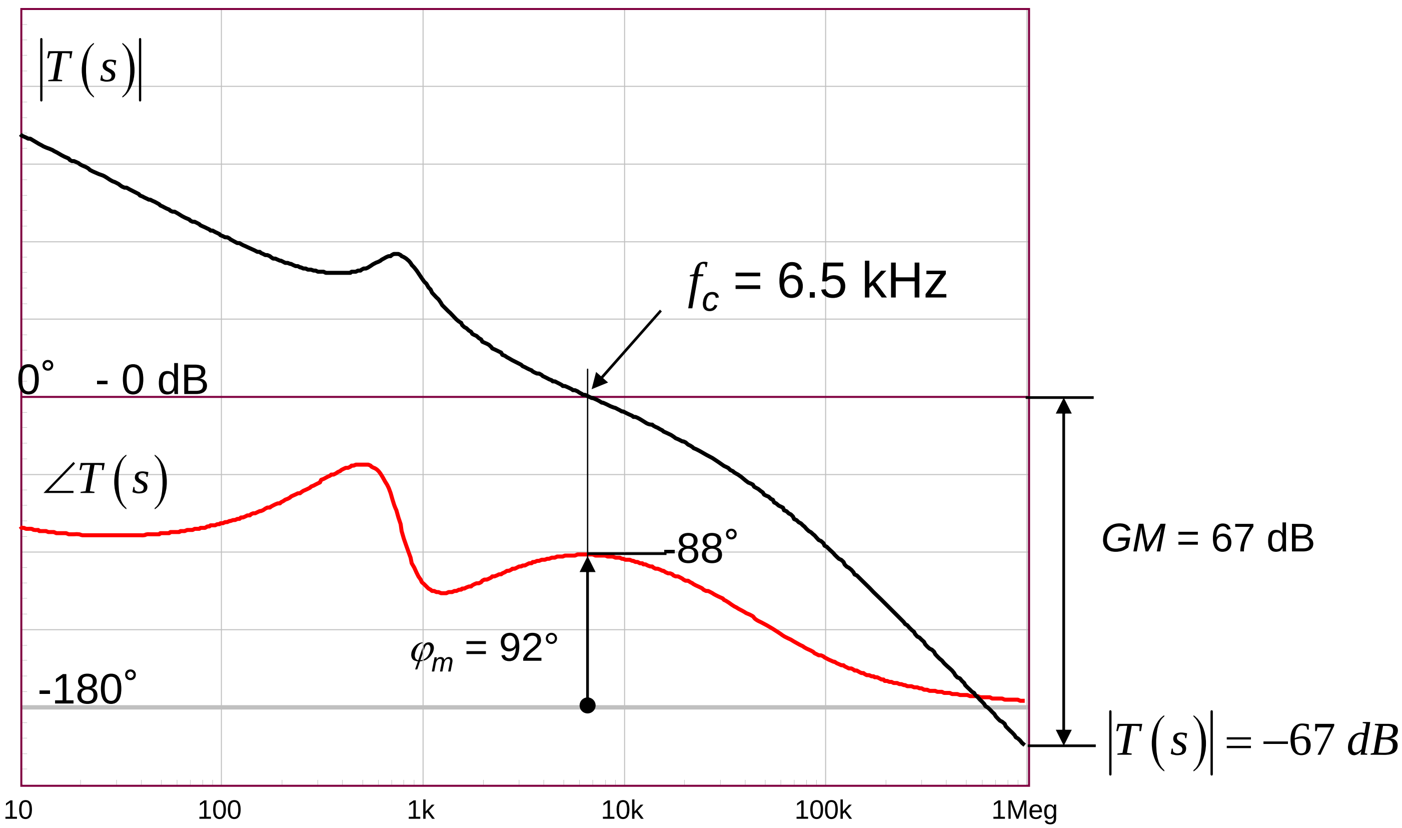
TL431

optocoupler



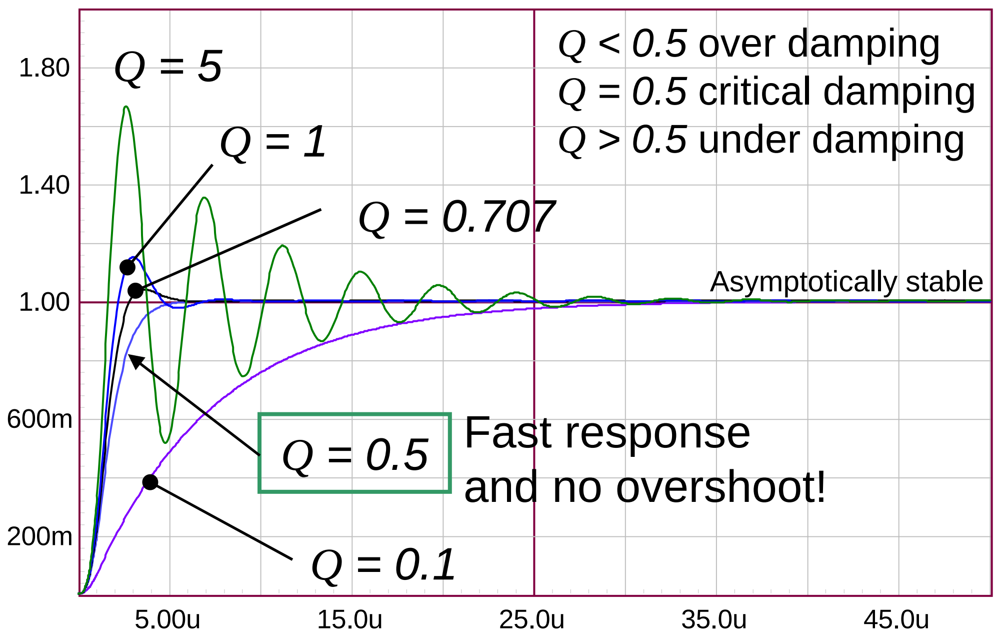
How do we Stabilize a Converter?

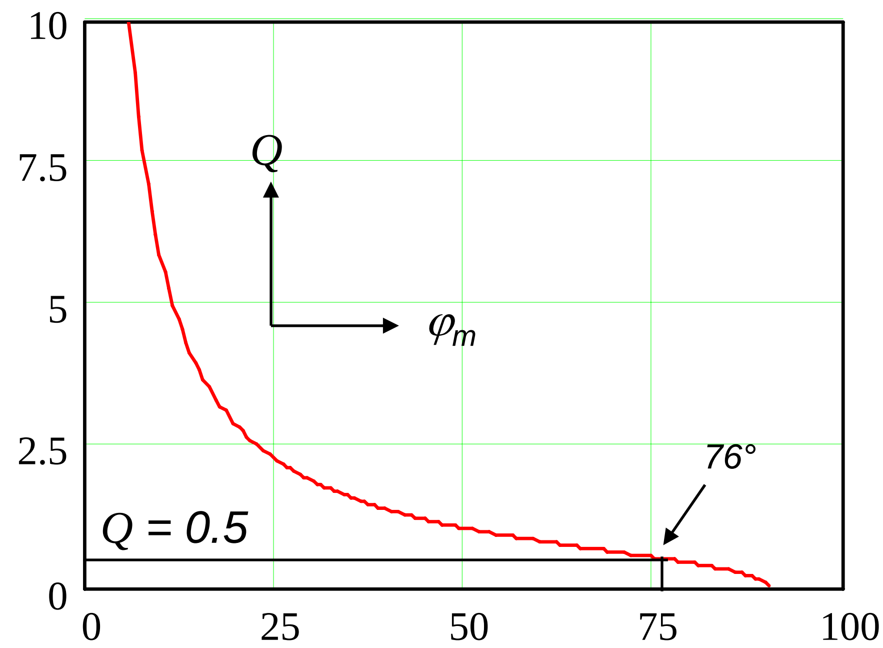
- ❑ We need a high gain at dc for a low static error
- ❑ We want a sufficiently high crossover frequency for response speed
- ➢ Shape the compensator $G(s)$ to build phase and gain margins!



How Much Phase Margin to Chose?

- a Q factor of 0.5 (critical response) implies a φ_m of 76°
- a 45° φ_m corresponds to a Q of 1.2: oscillatory response!



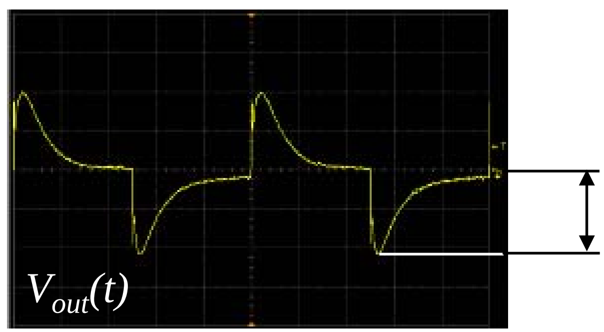


- phase margin depends on the needed response: fast, no overshoot…
- good practice is to shoot for 60° and make sure φ_m always > 45°

Which Crossover Frequency to Select?

❑ crossover frequency selection depends on several factors:

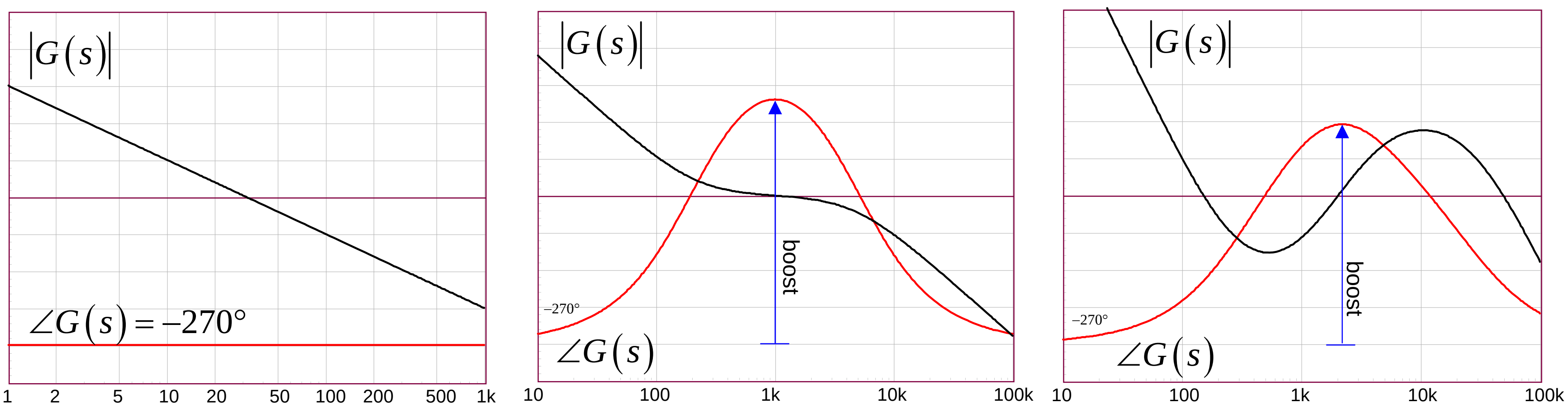
- *switching frequency*: theoretical limit is $F_{sw}/2$
- ➢ in practice, stay below 1/5 of F_{sw} for noise concerns
- *output ripple*: if ripple pollutes feedback, «tail chasing» can occur.
- ➢ crossover frequency rolloff is mandatory, e.g. in PFC circuits
- *presence of a Right-Half Plane Zero* (RHPZ):
- ➢ you cannot cross over beyond 30% of the lowest RHPZ position
- *output undershoot specification*:
- ➢ select crossover frequency based on undershoot specs



$$V_p \approx \frac{\Delta I_{out}}{2\pi f_c C_{out}}$$

What Compensator Types do we Need?

- ❑ There are basically 3 compensator types:
- ➢ type 1, 1 pole at the origin, no phase boost
- ➢ type 2, 1 pole at the origin, 1 zero, 1 pole. Phase boost up to 90°
- ➢ type 3, 1 pole at the origin, 1 zero pair, 1 pole pair. Boost up to 180°



Type 1 Type 2 Type 3

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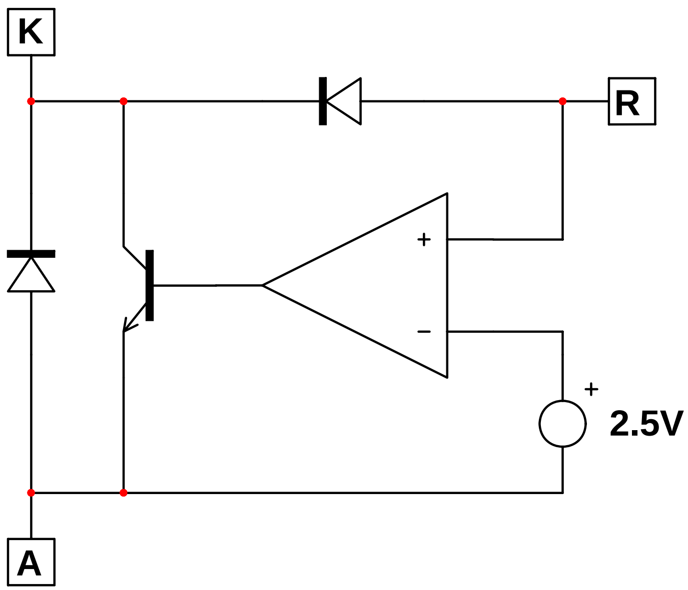
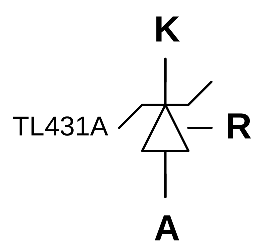
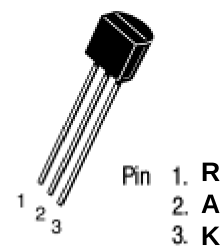
The TL431 Programmable Zener

- ❑ The TL431 is the most popular choice in nowadays designs
- ❑ It associates an open-collector op amp and a reference voltage
- ❑ The internal circuitry is self-supplied from the cathode current
- ❑ When the R node exceeds 2.5 V, it sinks current from its cathode



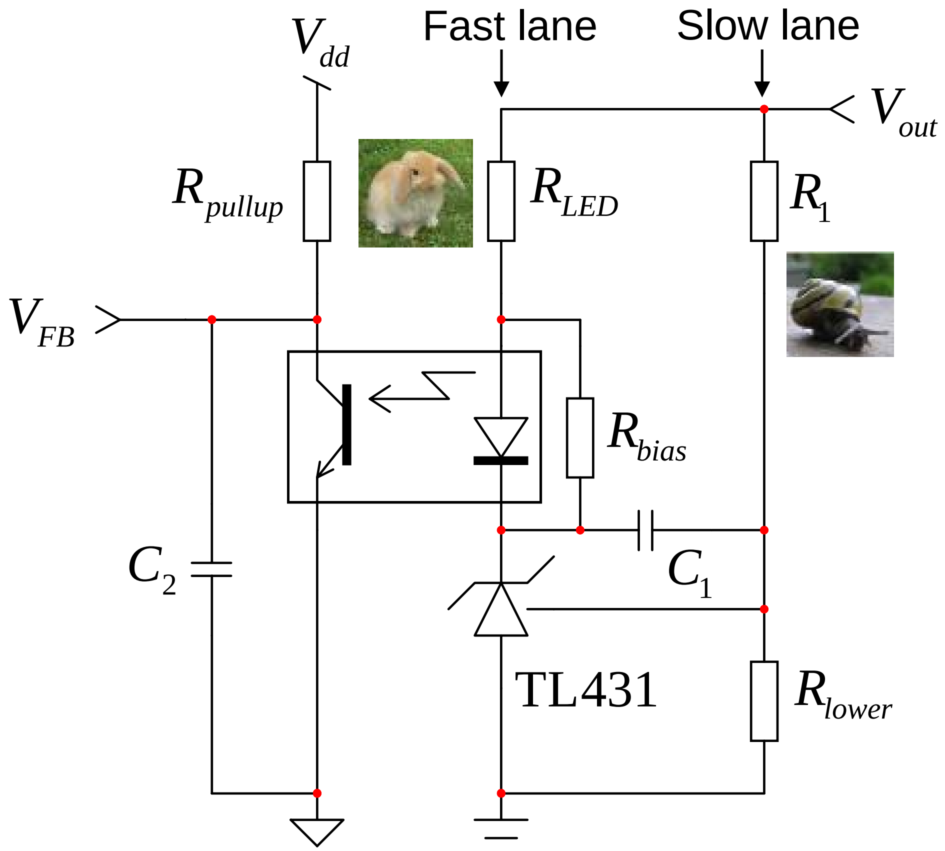


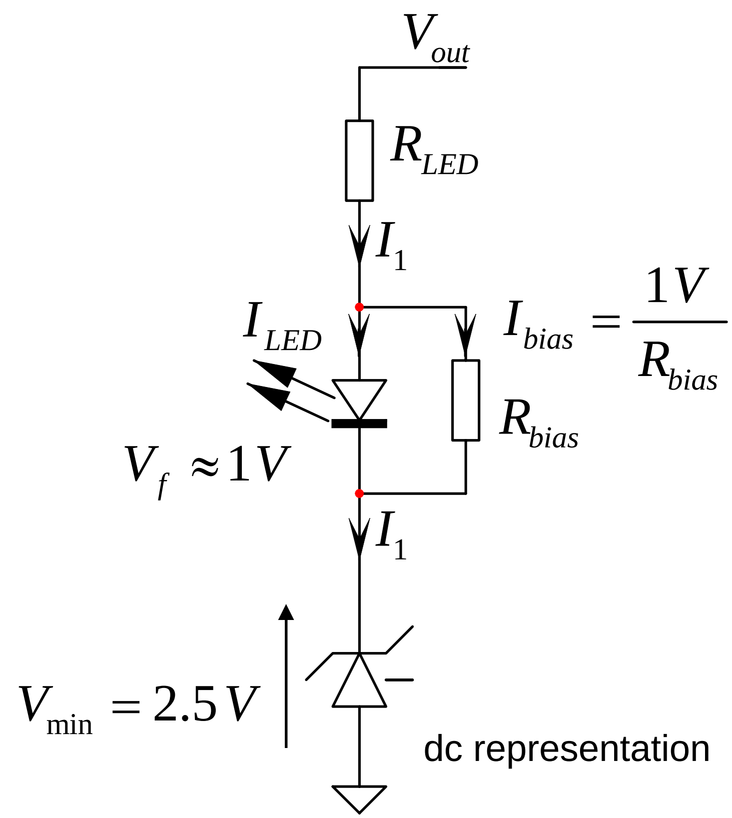


- ❑ The TL431 is a shunt regulator

The TL431 Programmable Zener

- ❑ The TL431 lends itself very well to optocoupler control





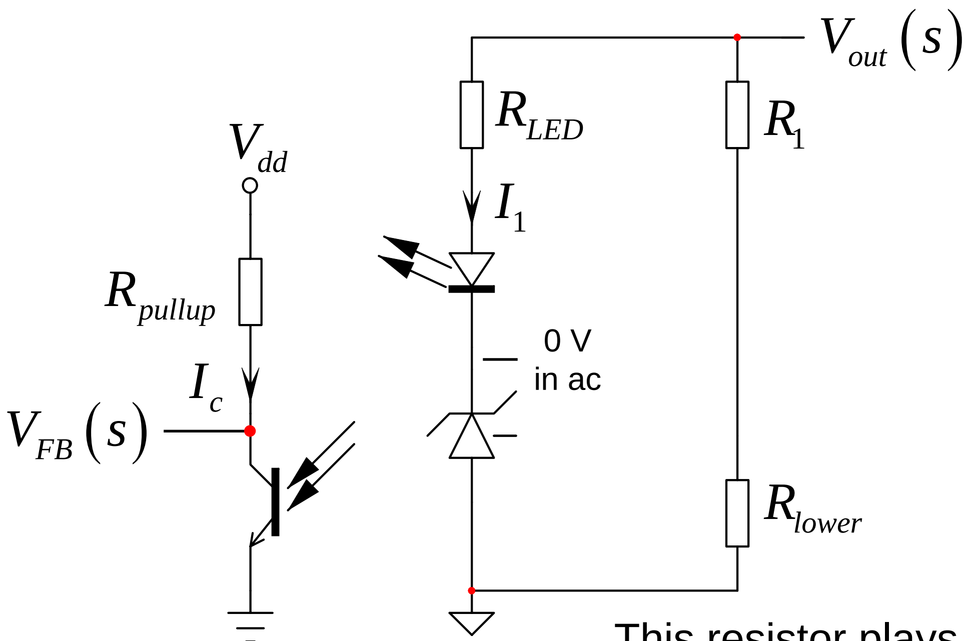
- ❑ R_{LED} must leave enough headroom over the TL431: upper limit!

The TL431 Programmable Zener

- ❑ This LED resistor is a design limiting factor in low output voltages:

$$R_{LED,\max} \le \frac{V_{out} - V_f - V_{TL431,\min}}{V_{dd} - V_{CE,sat} + I_{bias}\mathrm{CTR}_{\min} R_{pullup}} R_{pullup}\mathrm{CTR}_{\min}$$

- ❑ When the capacitor C_1 is a short-circuit, R_{LED} fixes the fast lane gain



$$V_{FB}(s) = -\mathrm{CTR} \cdot R_{pullup} \cdot I_1$$

$$I_1 = \frac{V_{out}(s)}{R_{LED}}$$

$$\frac{V_{FB}(s)}{V_{out}(s)} = -\mathrm{CTR}\frac{R_{pullup}}{R_{LED}}$$

This resistor plays a role in dc too!

The TL431 – the Static Gain Limit

- Let us assume the following design:

$$V_{out} = 5\,V$$
$$V_f = 1\,V$$
$$V_{TL431,\min} = 2.5\,V$$
$$V_{dd} = 4.8\,V$$
$$V_{CE,sat} = 300\,mV$$
$$I_{bias} = 1\,mA$$
$$\mathrm{CTR}_{\min} = 0.3$$
$$R_{pullup} = 20\,k\Omega$$

$$R_{LED,\max} \le \frac{5-1-2.5}{4.8-0.3+1m\times 0.3\times 20k}\times 20\mathrm{k}\times 0.3$$

$$R_{LED,\max} \le 857\,\Omega$$

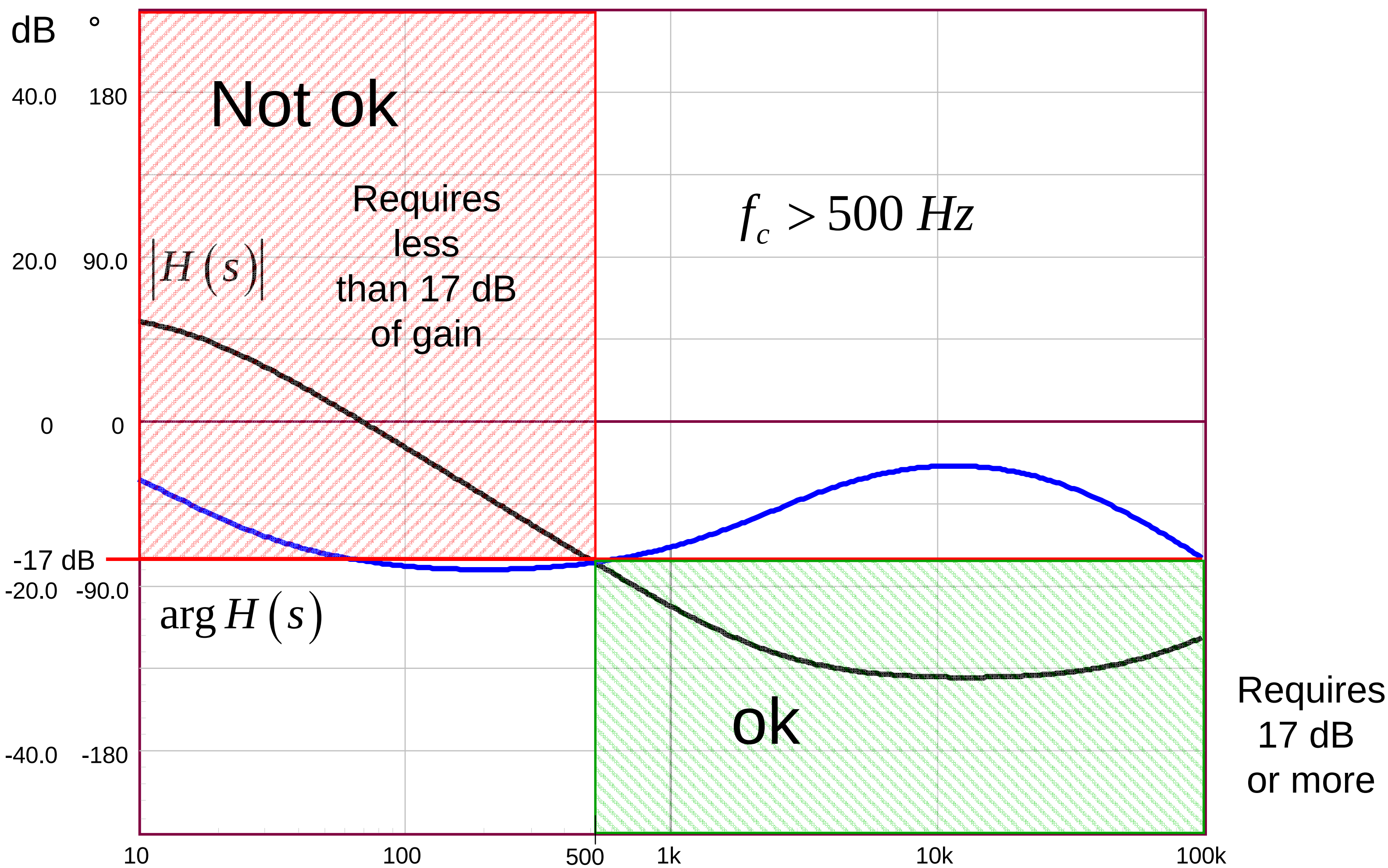
$$G_0 > \mathrm{CTR}\frac{R_{pullup}}{R_{LED}} > 0.3\frac{20}{0.857} > 7 \; or \approx 17\; dB$$

- In designs where R_{LED} fixes the gain, G_0 cannot be below 17 dB

⇨ You cannot “amplify” by less than 17 dB

The TL431 – the Static Gain Limit

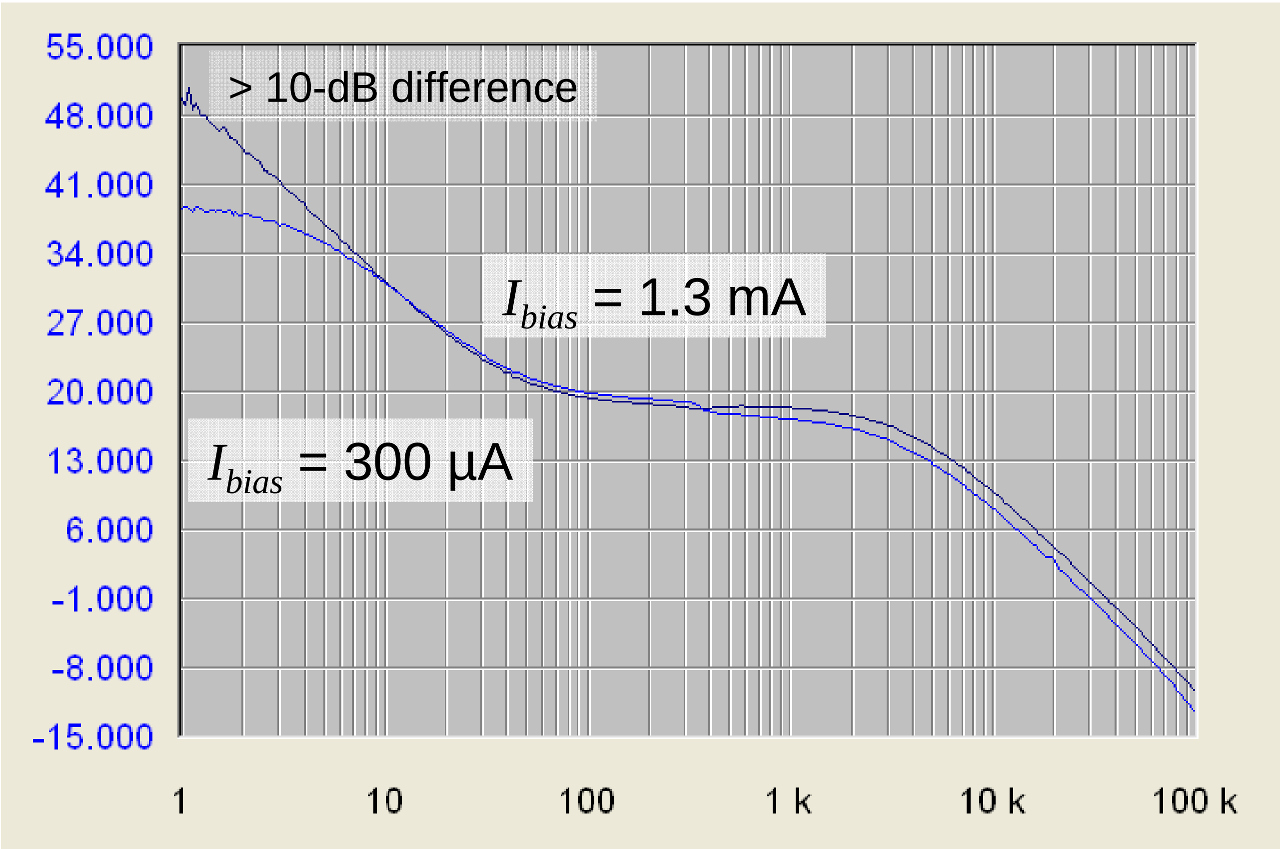
- ❑ You must identify the areas where compensation is possible

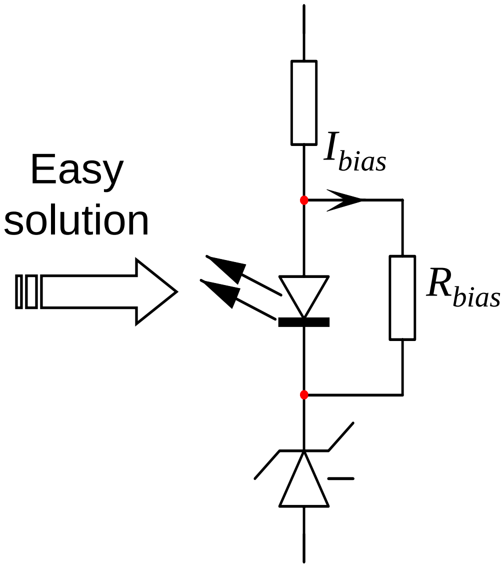


TL431 – Injecting Bias Current

- ❑ A TL431 must be biased above 1 mA to guaranty its parameters
- ❑ If not, its open-loop suffers – a 10-dB difference can be observed!

这里没有搞懂什么原因





$$R_{bias} = \frac{1}{1m} = 1\,k\Omega$$

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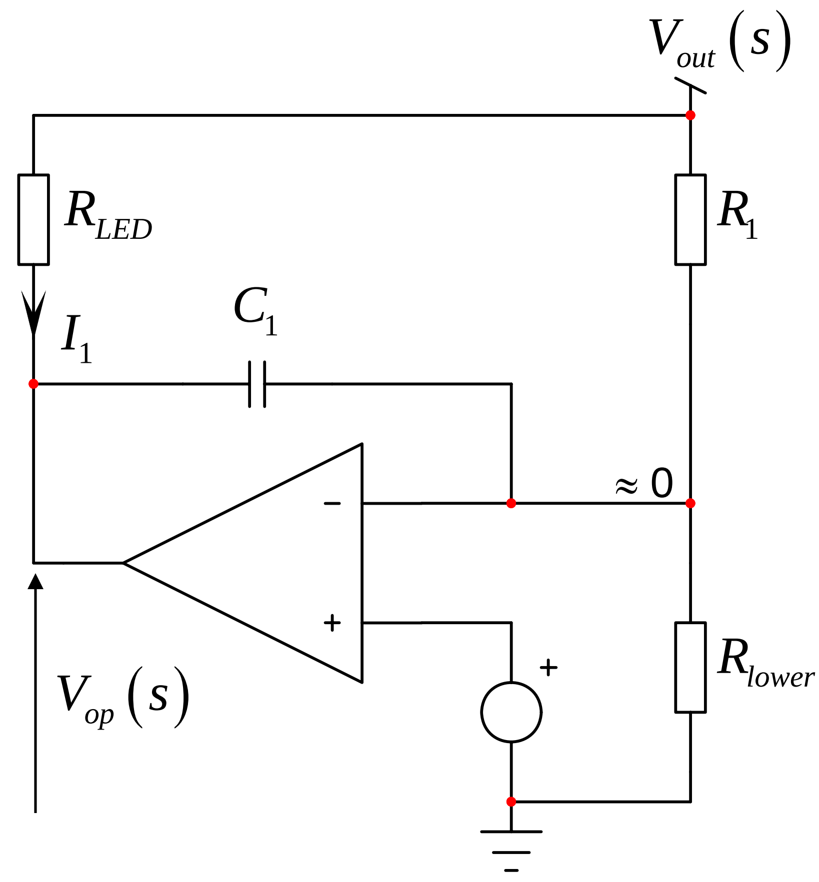
TL431 – Small-Signal Analysis

- ❑ The TL431 is an open-collector op amp with a reference voltage
- ❑ Neglecting the LED dynamic resistance, we have:



$$I_1(s) = \frac{V_{out}(s) - V_{op}(s)}{R_{LED}}$$

$$V_{op}(s) = -V_{out}(s)\frac{\frac{1}{sC_1}}{R_{upper}} = -V_{out}(s)\frac{1}{sR_{upper}C_1}$$

$$I_1(s) = V_{out}(s)\frac{1}{R_{LED}}\left[1 + \frac{1}{sR_{upper}C_1}\right]$$

We know that: $V_{FB}(s) = -\mathrm{CTR} \cdot R_{pullup} \cdot I_1$

$$\frac{V_{FB}(s)}{V_{out}(s)} = -\frac{R_{pullup}\mathrm{CTR}}{R_{LED}}\left[\frac{1 + sR_{upper}C_1}{sR_{upper}C_1}\right]$$

TL431 – Small-Signal Analysis

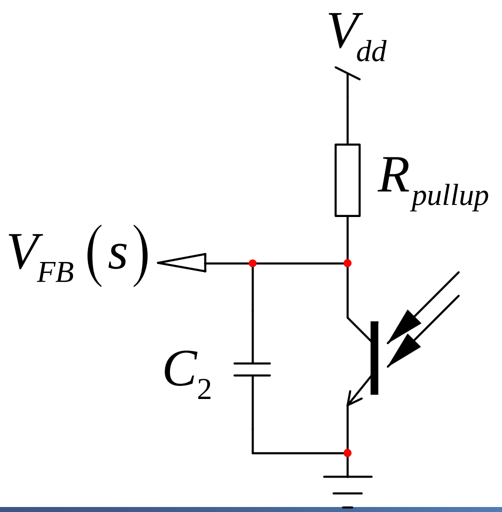
- ❑ In the previous equation we have:

✓ a static gain $G_0 = \mathrm{CTR}\dfrac{R_{pullup}}{R_{LED}}$

✓ a 0-dB origin pole frequency $\omega_{po} = \dfrac{1}{C_1 R_{upper}}$

✓ a zero $\omega_{z_1} = \dfrac{1}{R_{upper} C_1}$

- ❑ We are missing a pole for the type 2!

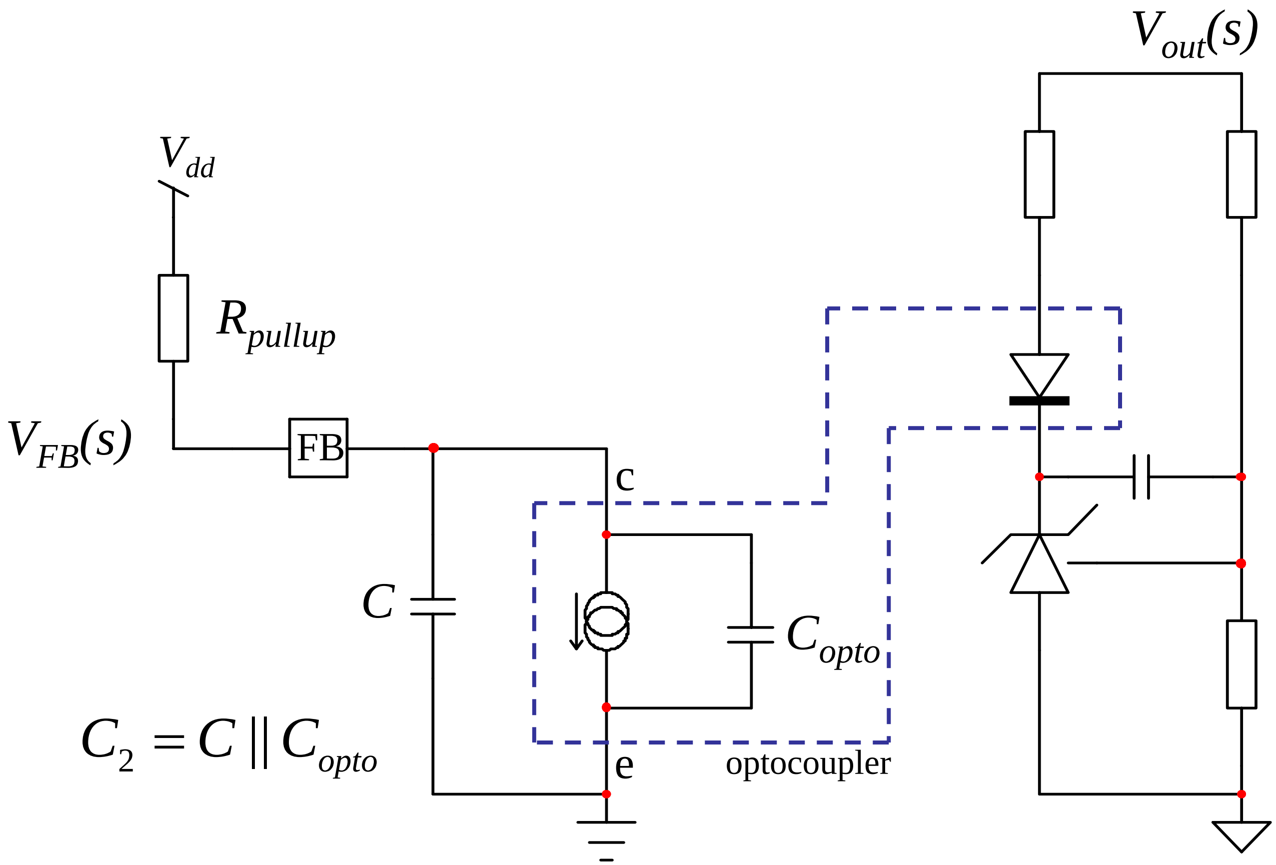


Add a cap. from collector to ground

$$\frac{V_{FB}(s)}{V_{out}(s)} = -\underbrace{\frac{R_{pullup}\mathrm{CTR}}{R_{LED}}\left[\frac{1+sR_{upper}C_1}{sR_{upper}C_1\left(1+sR_{pullup}C_2\right)}\right]}_{\text{Type 2 transfer function}}$$

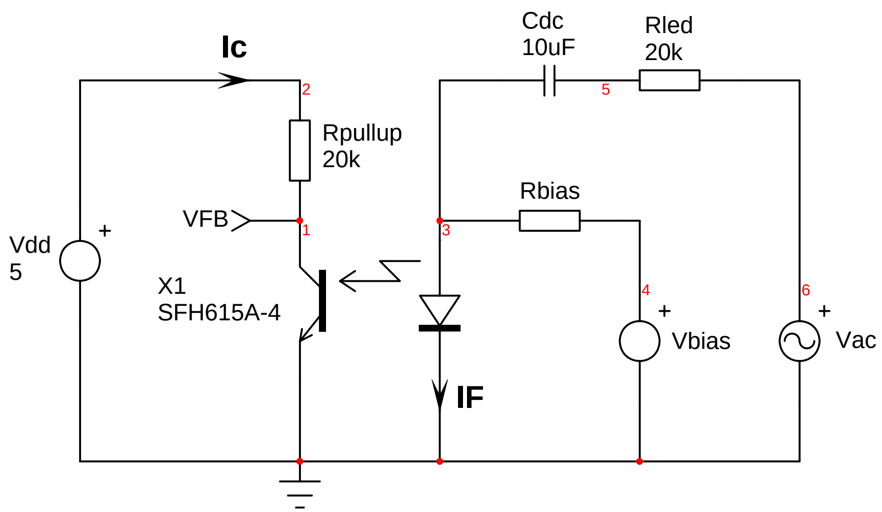
TL431 – Small-Signal Analysis

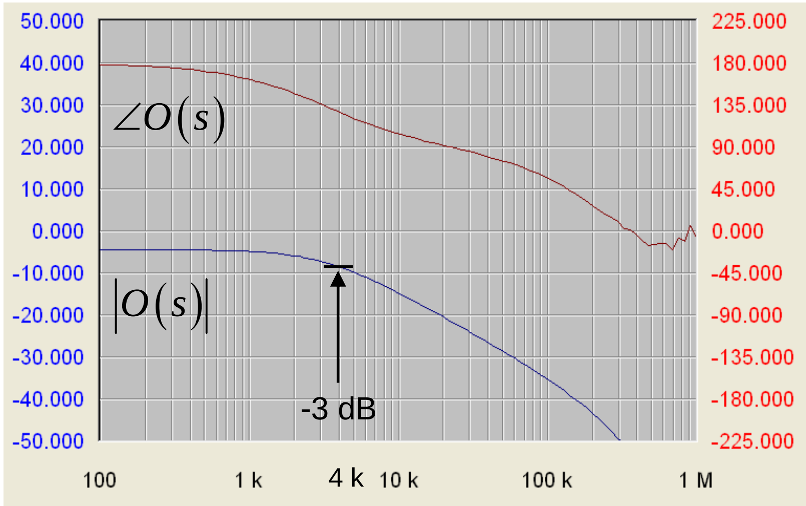
- ❑ The optocoupler also features a parasitic capacitor
- ➢ it comes in parallel with C_2 and must be accounted for



TL431 – Small-Signal Analysis

- ❑ The optocoupler must be characterized to know where its pole is





- ❑ Adjust V_{bias} to have V_{FB} at 2-3 V to be in linear region, then ac sweep
- ❑ The pole in this example is found at 4 kHz

$$C_{opto} = \frac{1}{2\pi R_{pullup} f_{pole}} = \frac{1}{6.28 \times 20k \times 4k} \approx 2\ nF$$

⇨ Another design constraint!

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The TL431 in a Type 1 Compensator

- To make a type 1 (origin pole only) neutralize the zero and the pole

$$\frac{V_{FB}(s)}{V_{out}(s)} = -\frac{R_{pullup}\mathrm{CTR}}{R_{LED}}\left[\frac{\boxed{1+sR_{upper}C_1}}{sR_{upper}C_1\left(\boxed{1+sR_{pullup}C_2}\right)}\right]$$

$$sR_{upper}C_1 = sR_{pullup}C_2 \Longrightarrow C_1 = \frac{R_{pullup}}{R_{upper}}C_2 \xRightarrow{\text{substitute}} \omega_{po} = \frac{1}{\dfrac{R_{upper}R_{LED}}{R_{pullup}\mathrm{CTR}}C_1}$$

$$\omega_{po} = \frac{\mathrm{CTR}}{C_2 R_{LED}} \Longrightarrow C_2 = \frac{\mathrm{CTR}}{2\pi f_{po} R_{LED}}$$

- Once neutralized, you are left with an integrator

$$G(s) = \frac{1}{\dfrac{s}{\omega_{po}}} \longrightarrow |G(f_c)| = \frac{f_{po}}{f_c} \longrightarrow f_{po} = G_{f_c} f_c \Longrightarrow C_2 = \frac{\mathrm{CTR}}{2\pi G_{f_c} f_c R_{LED}}$$

TL431 Type 1 Design Example

- We want a 5-dB gain at 5 kHz to stabilize the 5-V converter

$$\left.\begin{aligned}
V_{out} &= 5\,V \\
V_f &= 1\,V \\
V_{TL431,\min} &= 2.5\,V \\
V_{dd} &= 4.8\,V \\
V_{CE,sat} &= 300\,mV \\
I_{bias} &= 1\,mA \\
\mathrm{CTR}_{\min} &= 0.3 \\
R_{pullup} &= 20\,k\Omega
\end{aligned}\right\} \; R_{LED,\max} \le 857\,\Omega \xrightarrow{\text{Apply 15\% margin}} R_{LED} = 728\,\Omega$$

$$\left.\begin{aligned}
G_{fc} &= 10^{\frac{5}{20}} = 1.77 \\
f_c &= 10\,kHz
\end{aligned}\right\} \; C_2 = \frac{\mathrm{CTR}}{2\pi G_{f_c} f_c R_{LED}} = \frac{0.3}{6.28 \times 1.77 \times 5k \times 728} \approx 7.4\,nF$$

C_{opto} = 2 nF

$$\Rightarrow \quad C = 7.4n - 2n = 5.4\,nF \qquad C_1 = \frac{R_{pullup}}{R_{upper}} C_2 \approx 14.7\,nF$$

TL431 Type 1 Design Example

- SPICE can simulate the design – automate elements calculations…

parameters

Vout=5

Vf=1
Vref=2.5
VCEsat=300m
Vdd=4.8
Ibias=1m

A=Vout-Vf-Vref
B=Vdd-VCEsat+Ibias*CTR*Rpullup
Rmax=(A/B)*Rpullup*CTR

Rupper=(Vout-2.5)/250u
fc=5k
Gfc=-5

G=10^(-Gfc/20)
pi=3.14159

Fpo=G*fc

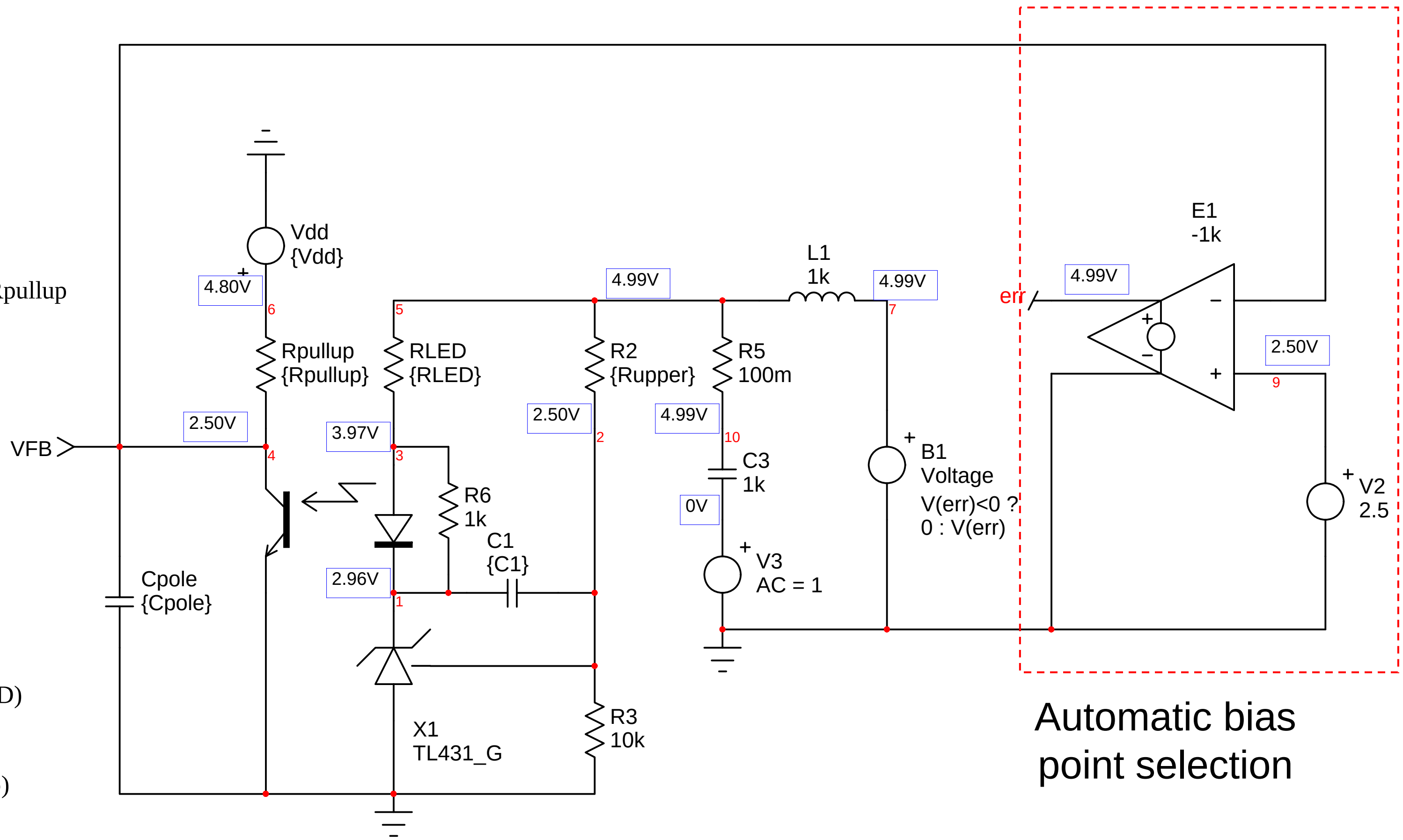
Rpullup=20k

RLED=Rmax*0.85

C1=Cpole1*Rpullup/Rupper

Cpole1=CTR/(2*pi*Fpo*RLED)
Cpole=Cpole1-Copto

Fopto=4k
Copto=1/(2*pi*Fopto*Rpullup)
CTR = 0.3



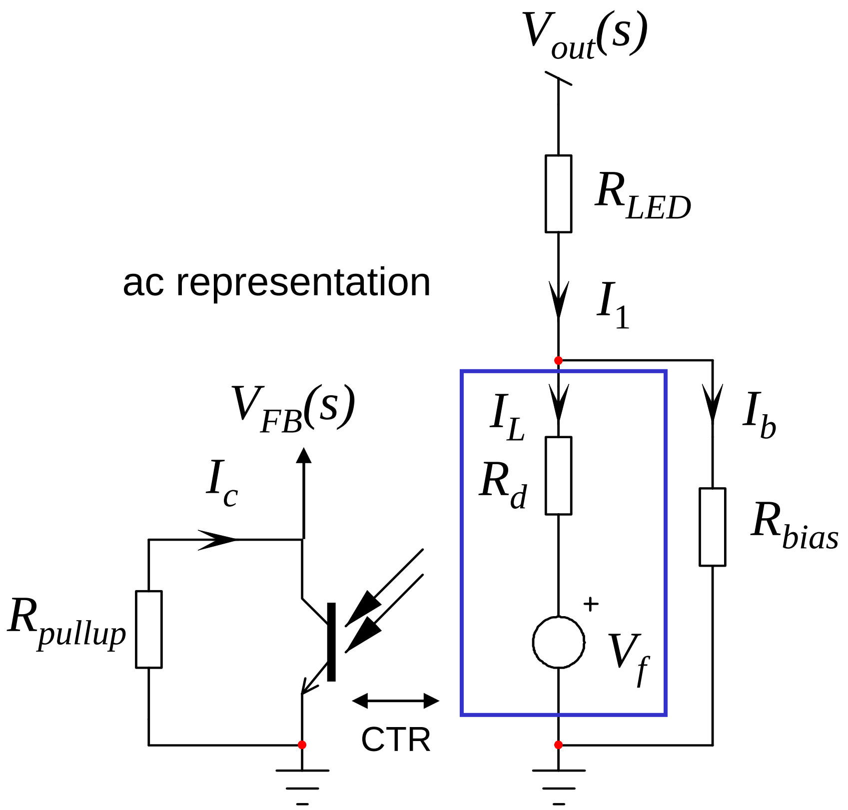
Automatic bias point selection

TL431 Type 1 Design Example

- We have a type 1 but 1.3 dB of gain is missing? Hu?

TL431 Type 1 Design Example

- The 1-kΩ resistor in parallel with the LED is an easy bias
- However, as it appears in the loop, does it affect the gain?



$$V_{FB} = I_c R_{pullup} = I_L R_{pullup} \mathrm{CTR}$$

$$I_L = I_1 \frac{R_{bias}}{R_{bias} + R_d}$$

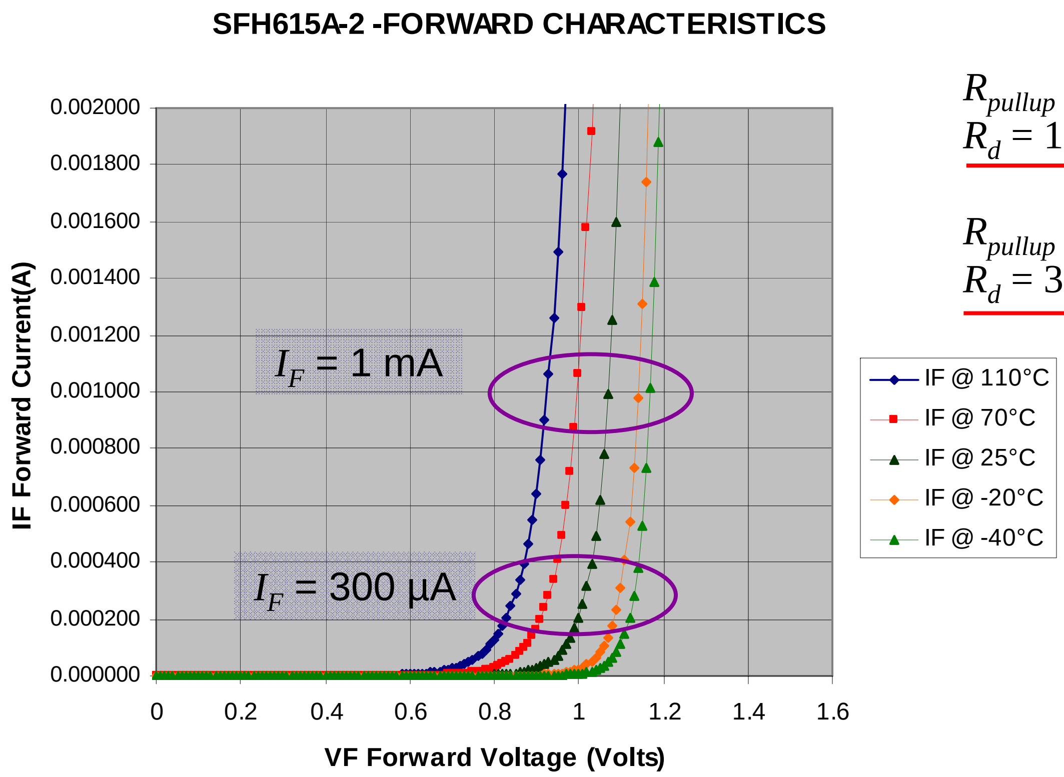
$$I_L = \frac{V_{out}}{R_{LED} + R_{bias} \parallel R_d} \frac{R_{bias}}{R_{bias} + R_d}$$

$$\left.\frac{V_{FB}}{V_{out}}\right|_{s=0} = \frac{R_{pullup}\mathrm{CTR}}{R_{LED} + R_{bias} \parallel R_d} \frac{R_{bias}}{R_{bias} + R_d}$$

- Both bias and dynamic resistances have a role in the gain expression

TL431 Type 1 Design Example

- A low operating current increases the dynamic resistor



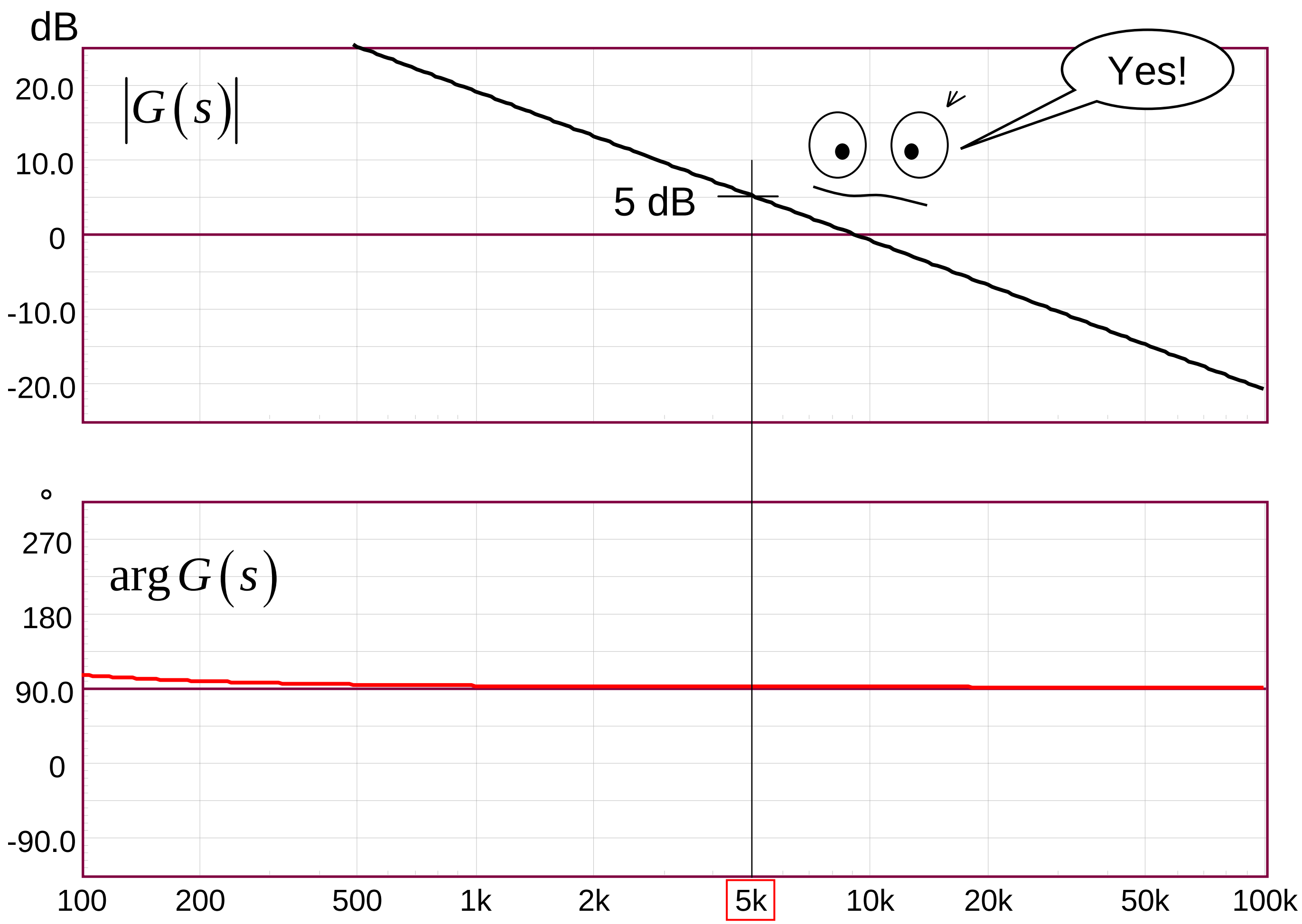
R_{pullup} = 20 kΩ, I_F = 300 µA (CTR = 0.3)
R_d = 158 Ω

R_{pullup} = 1 kΩ, I_F = 1 mA (CTR = 1)
R_d = 38 Ω

- Make sure you have enough LED current to reduce its resistance

TL431 Type 1 Design Example

- The pullup resistor is 1 kΩ and the target now reaches 5 dB



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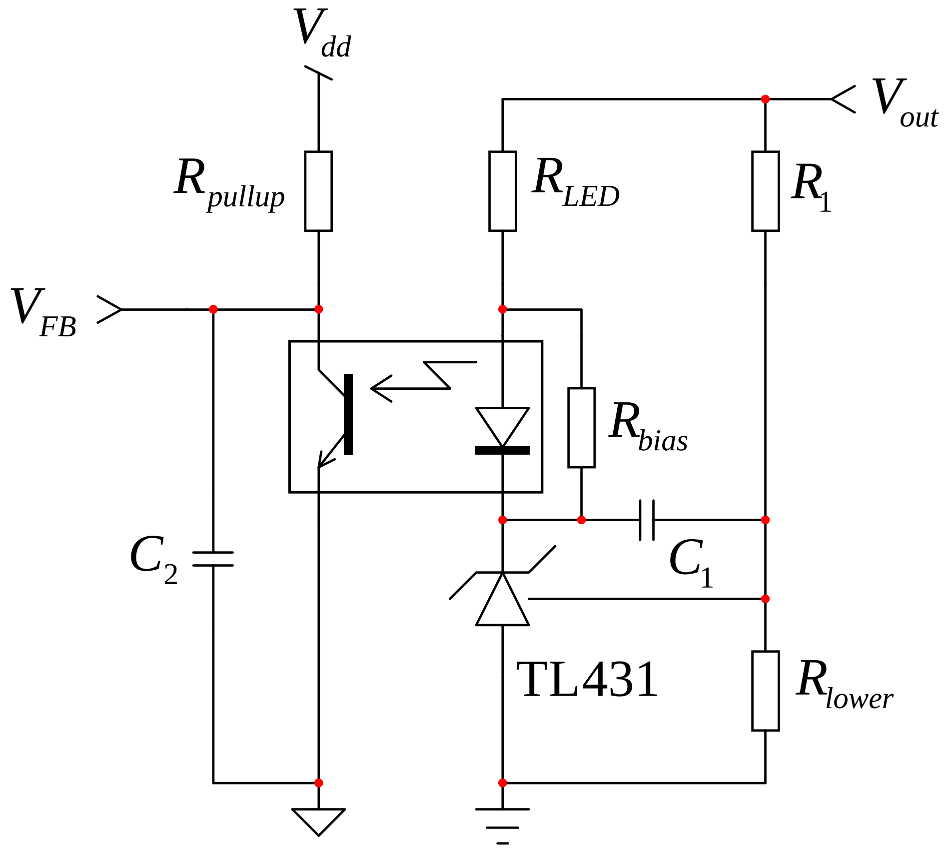
The TL431 in a Type 2 Compensator

- Our first equation was already a type 2 definition, we are all set!



$$G_0 = \mathrm{CTR}\frac{R_{pullup}}{R_{LED}}$$

$$\omega_{z_1} = \frac{1}{R_{upper}C_1}$$

$$\omega_{p_1} = \frac{1}{R_{pullup}C_2}$$

- Just make sure the optocoupler contribution is involved…

TL431 Type 2 Design Example

- You need to provide a 15-dB gain at 5 kHz with a 50° boost

$$f_p = \left[\tan\left(boost\right) + \sqrt{\tan^2\left(boost\right)+1}\right] f_c = 2.74 \times 5k = 13.7\ kHz$$

$$f_z = f_c^{\ 2} / f_p = 25k/13.7k \approx 1.8\ kHz \qquad G_0 = \mathrm{CTR}\,\frac{R_{pullup}}{R_{LED}} = 10^{15/20} = 5.62$$

- With a 250-µA bridge current, the divider resistor is made of:

$$R_{lower} = 2.5/250u = 10\ k\Omega \qquad R_1 = \left(12-2.5\right)/250u = 38\ k\Omega$$

- The pole and zero respectively depend on R_{pullup} and R_1:

$$C_2 = 1/2\pi f_p R_{pullup} = 581\ pF \qquad C_1 = 1/2\pi f_z R_1 = 2.3\ nF$$

- The LED resistor depends on the needed mid-band gain:

$$R_{LED} = \frac{R_{pullup}\mathrm{CTR}}{G_0} = 1.06\ k\Omega \xrightarrow{\text{ok}} R_{LED,\max} \le 4.85\ k\Omega$$

TL431 Type 2 Design Example

- The optocoupler is still at a 4-kHz frequency:

$$C_{pole} \approx \boxed{2\ nF}$$

Already above!

- Type 2 pole capacitor calculation requires a $\boxed{\text{581 pF}}$ cap.!

⇨ The bandwidth cannot be reached, reduce f_c!

- For noise purposes, we want a minimum of 100 pF for C
- With a total capacitance of 2.1 nF, the highest pole can be:

$$f_{pole} = \frac{1}{2\pi R_{pullup} C} = \frac{1}{6.28 \times 20k \times 2.1n} = 3.8\ kHz$$

- For a 50° phase boost and a 3.8-kHz pole, the crossover must be:

$$f_c = \frac{f_p}{\tan(boost) + \sqrt{\tan^2(boost) + 1}} \approx 1.4\ kHz$$

TL431 Type 2 Design Example

- The zero is then simply obtained:

$$f_z = \frac{f_c^{\,2}}{f_p} = 516\ Hz$$

- We can re-derive the component values and check they are ok

$$C_2 = 1/2\pi f_p R_{pullup} = 2.1\,nF \qquad C_1 = 1/2\pi f_z R_1 = 8.1\,nF$$

- Given the 2-nF optocoupler capacitor, we just add 100 pF

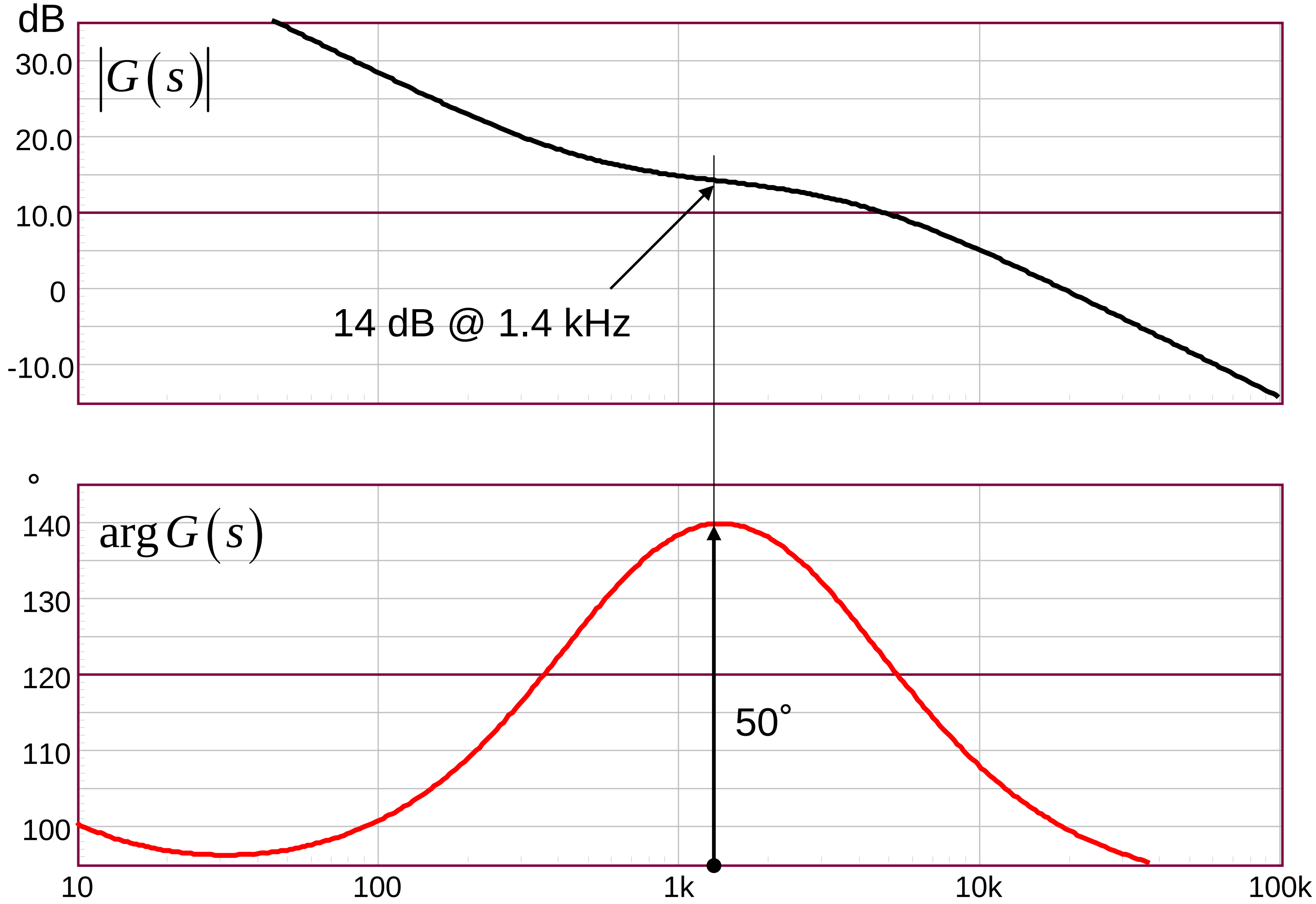
- In this example, $R_{LED,max}$ is 4.85 kΩ

$$G_0 > \mathrm{CTR}\frac{R_{pullup}}{R_{LED}} > 0.3\frac{20}{4.85} > 1.2\ or \approx 1.8\ dB$$

- You <u>cannot</u> use this type 2 if an attenuation is required at f_c!

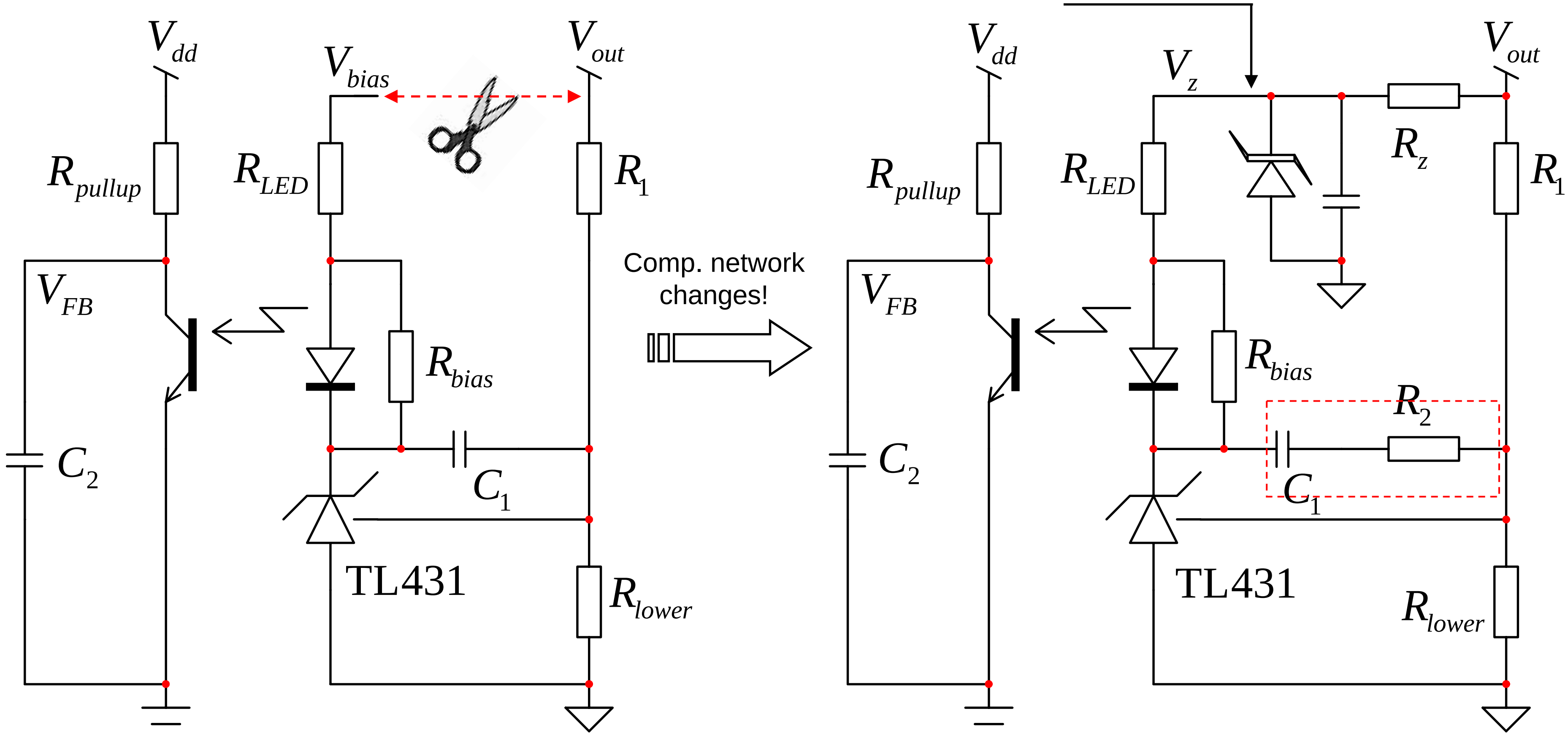
TL431 Type 2 Design Example

- The 1-dB gain difference is linked to R_d and the bias current



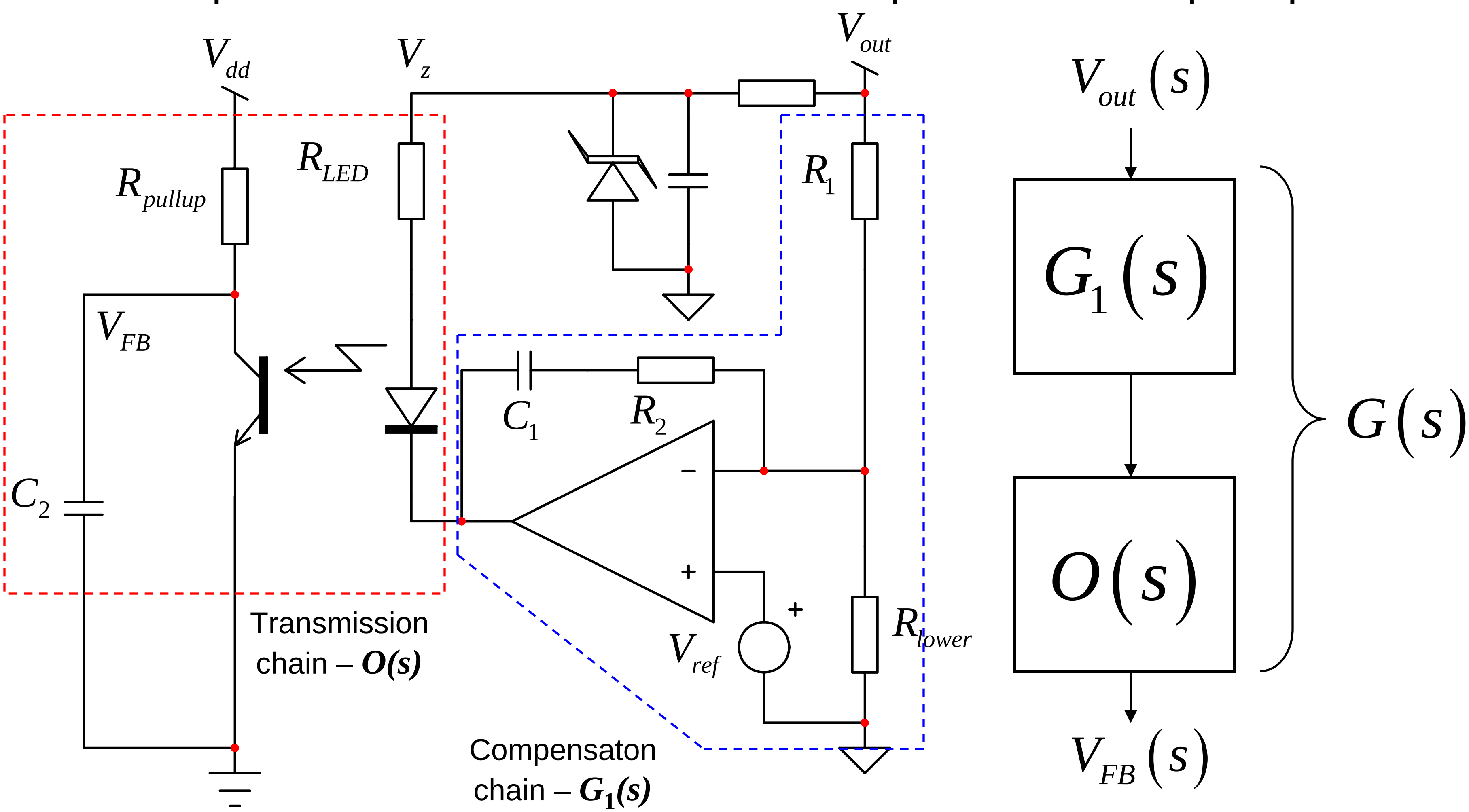
TL431 – Suppressing the Fast Lane

- ❑ The gain limit problem comes from the fast lane presence
- ❑ Its connection to V_{out} creates a parallel input
- ➢ The solution is to hook the LED resistor to a fixed bias



TL431 – Suppressing the Fast Lane

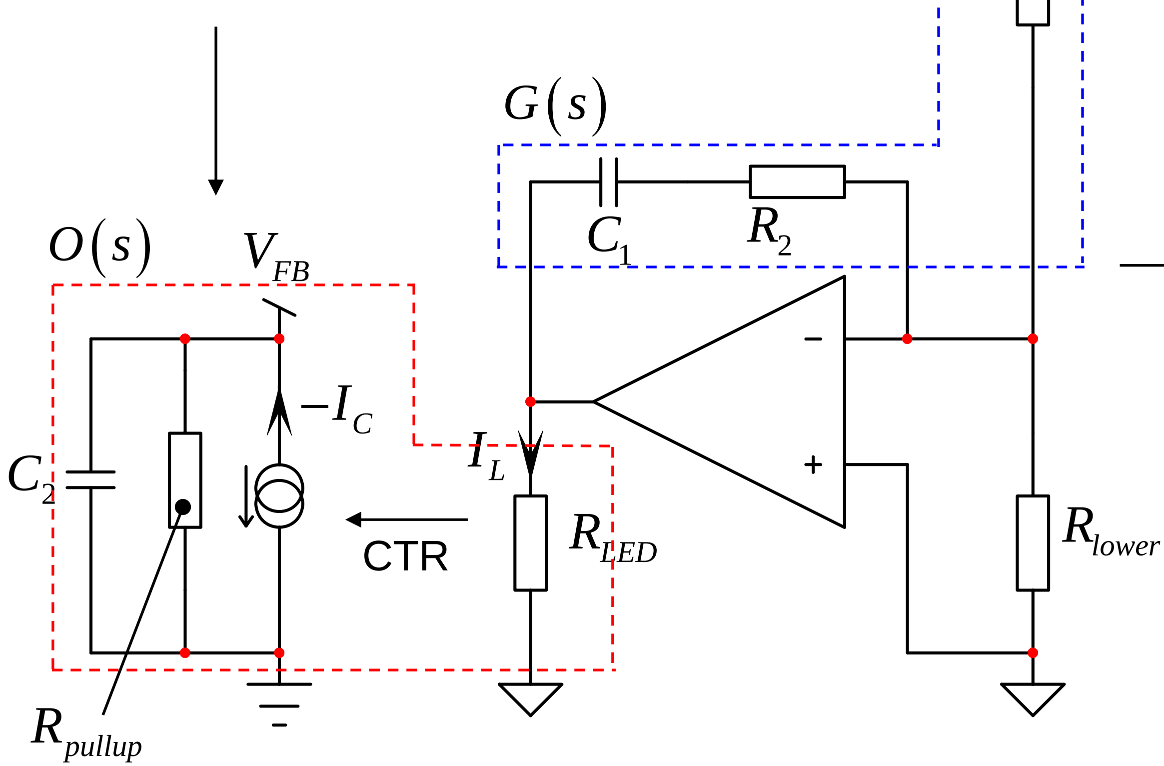
- The equivalent schematic becomes an open-collector op amp



TL431 – Suppressing the Fast Lane

- ❑ The small-signal ac representation puts all sources to 0

$$O(s) = \frac{R_{pullup}}{R_{LED}} \mathrm{CTR} \frac{1}{1 + sR_{pullup}C_{pole}}$$



$$G_1(s) = \frac{1 + \mathrm{R}_2\mathrm{C}_1}{sR_1C_1}$$

TL431 – Suppressing the Fast Lane

- ❑ The op amp can now be wired in any configuration!
- ❑ Just keep in mind the optocoupler transmission chain

$$O(s) = \frac{R_{pullup}}{R_{LED}} \mathrm{CTR} \frac{1}{1 + sR_{pullup}C_{pole}}$$

- ❑ Wire the op amp in type 2A version (no high frequency pole)

$$G_1(s) = \frac{1 + \mathrm{R}_2\mathrm{C}_1}{sR_1C_1}$$

- ❑ When cascaded, you obtain a type 2 with an extra gain term

$$G(s) = \underbrace{\boxed{\frac{R_{pullup}}{R_{LED}} \mathrm{CTR}}}_{G_2} \frac{1 + R_2C_1}{sR_1C_1\left(1 + sR_{pullup}C_{pole}\right)}$$

TL431 Type 2 Design Example – No Fast Lane

- We still have a constraint on R_{LED} but only for dc bias purposes

$$R_{LED,\max} \leq \frac{\boxed{V_z} - V_f - V_{TL431,\min}}{V_{dd} - V_{CE,sat} + I_{bias}\mathrm{CTR}_{\min} R_{pullup}} R_{pullup}\mathrm{CTR}_{\min}$$

- You need to <u>attenuate</u> by -10-dB at 1.4 kHz with a 50° boost
- The poles and zero position are that of the previous design

$$\left.\begin{aligned}
V_z &= 6.2\,V \\
V_f &= 1\,V \\
V_{TL431,\min} &= 2.5\,V \\
V_{dd} &= 4.8\,V \\
V_{CE,sat} &= 300\,mV \\
I_{bias} &= 1\,mA \\
\mathrm{CTR}_{\min} &= 0.3 \\
R_{pullup} &= 20\,k\Omega
\end{aligned}\right\} R_{LED,\max} \leq 1.5\,k\Omega \xrightarrow{\text{Apply 15\% margin}} R_{LED} = 1.27\,k\Omega$$

$$f_z = 516\,Hz \quad f_p = 3.8\,kHz$$

TL431 Type 2 Design Example – No Fast Lane

- ❑ We need to account for the extra gain term:

$$G_2 = \frac{R_{pullup}}{R_{LED}} \mathrm{CTR} = \frac{20\mathrm{k}}{1.27\mathrm{k}} 0.3 = 4.72$$

- ❑ The required total mid-band attenuation at 1.4 kHz is -10 dB

$$G_{f_c} = 10^{-10/20} = 0.316$$

- ❑ The mid-band gain from the type 2A is therefore:

$$G_1 = \frac{G_0}{G_2} = \frac{0.316}{4.72} = 0.067 \text{ or } -23.5\,dB$$

- ❑ Calculate R_2 for this attenuation:

$$R_2 = G_1 R_1 \frac{\sqrt{\left(\frac{f_c}{f_p}\right)^2 + 1}}{\sqrt{\left(\frac{f_z}{f_c}\right)^2 + 1}} = 2.6\,k\Omega$$

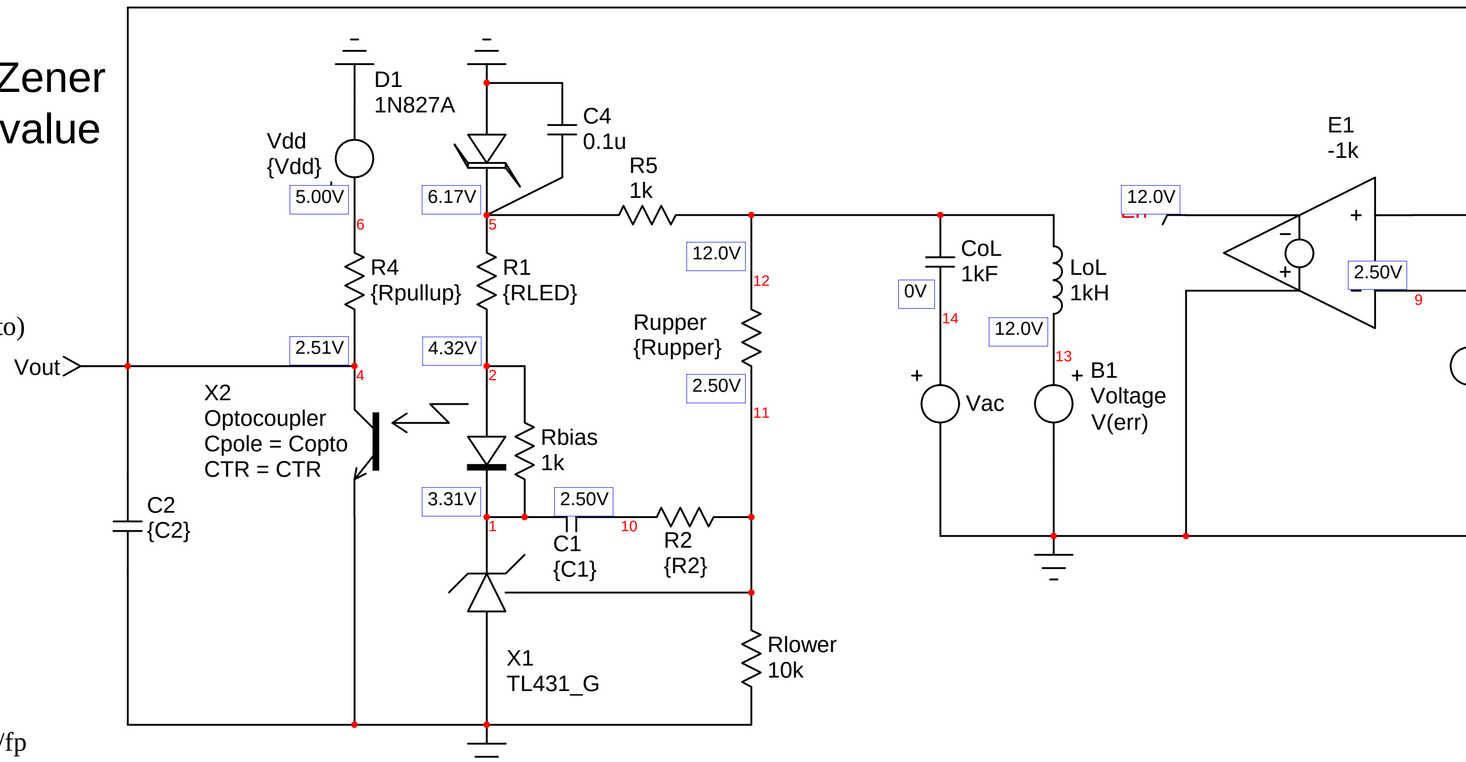
TL431 Type 2 Design Example – No Fast Lane

- ❑ An automated simulation helps to test the calculation results

parameters

Vout=12
Rupper=(Vout-2.5)/250u
fc=1.4k
Gfc=10
Vf=1
Ibias=1m
Vref=2.5
VCEsat=300m
Vdd=5
Vz=6.2
Rpullup=20k
Fopto=4k
Copto=1/(2*pi*Rpullup*Fopto)
CTR=0.3
G1=Rpullup*CTR/RLED
G2=10^(-Gfc/20)
G=G2/G1
pi=3.14159
fz=516
fp=3.8k
C1=1/(2*pi*fz*R2)
Cpole2=1/(2*pi*fp*Rpullup)
C2=Cpole2-Copto
a=(fz^2+fc^2)*(fp^2+fc^2)
c=(fz^2+fc^2)
R2=(sqrt(a)/c)*G*fc*Rupper/fp
Rmax1=(Vz-Vf-Vref)
Rmax2=(Vdd-VCEsat+Ibias*(Rpullup*CTR))
RLED=(Rmax1/Rmax2)*Rpullup*CTR*0.85

Zener value



TL431 Type 2 Design Example – No Fast Lane

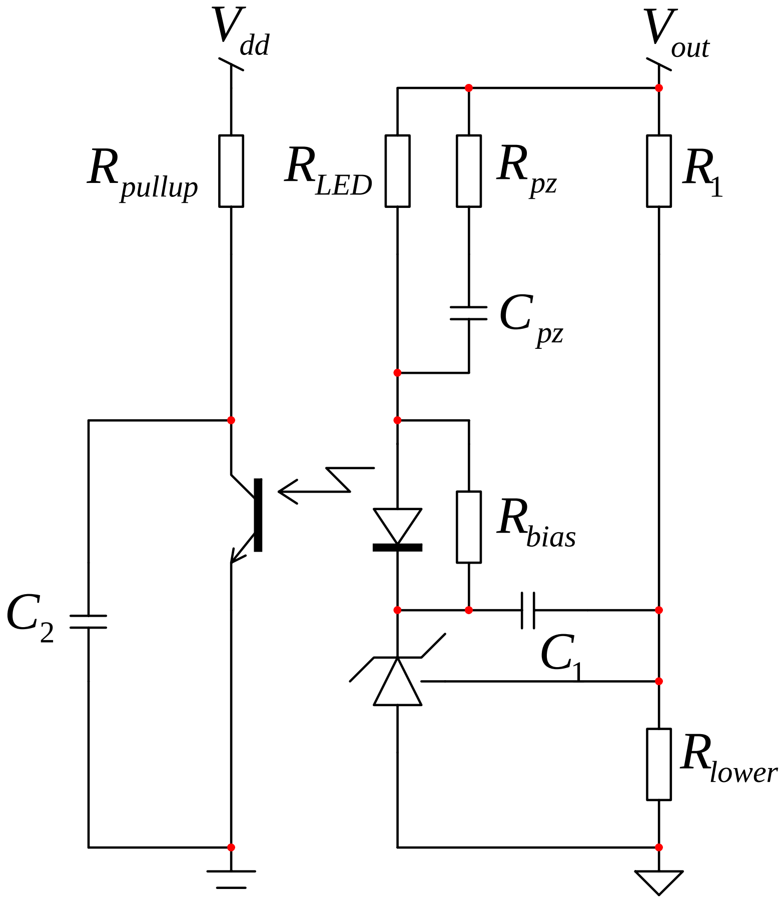
- ❑ The simulation results confirm the calculations are ok

Agenda

- Feedback generalities
- The TL431 in a compensator
- Small-signal analysis of the return chain
- A type 1 implementation with the TL431
- A type 2 implementation with the TL431
- **A type 3 implementation with the TL431**
- Design examples
- Conclusion

The TL431 in a Type 3 Compensator

❑ The type 3 with a TL431 is difficult to put in practice



$$f_{z_1} = \frac{1}{2\pi R_1 C_1} \qquad f_{z_2} = \frac{1}{2\pi \left(\boxed{R_{LED}} + R_{pz}\right) C_{pz}}$$

$$f_{p_1} = \frac{1}{2\pi R_{pz} C_{pz}} \qquad f_{p_2} = \frac{1}{2\pi R_{pullup} \left(C_2 \parallel C_{opto}\right)}$$

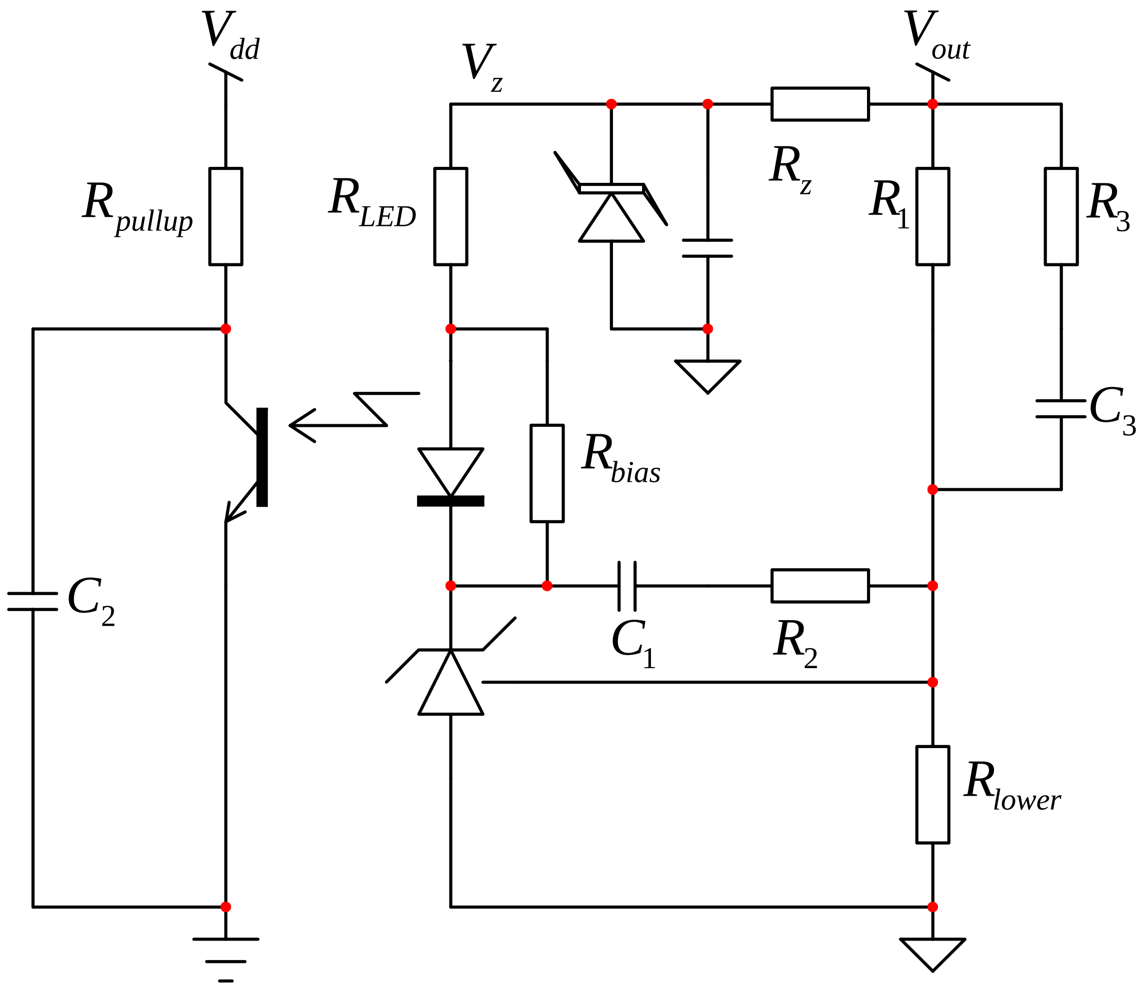
$$G = \frac{R_{pullup}}{\boxed{R_{LED}}} \mathrm{CTR}$$

R_{LED} fixes the gain and a zero position

❑ Suppress the fast lane for an easier implementation!

The TL431 in a Type 3 Compensator

- Once the fast lane is removed, you have a classical configuration



$$f_{z_1} = \frac{1}{2\pi R_2 C_1}$$

$$f_{z_2} = \frac{1}{2\pi R_1 C_3}$$

$$f_{p_1} = \frac{1}{2\pi R_3 C_3}$$

$$f_{p_2} = \frac{1}{2\pi R_{pullup}\left(C_2 \parallel C_{opto}\right)}$$

$$G = \frac{R_{pullup}}{R_{LED}}\mathrm{CTR}$$

TL431 Type 3 Design Example – No Fast Lane

- ❑ We want to provide a 10-dB attenuation at 1 kHz
- ❑ The phase boost needs to be of 120°
- ➢ place the double pole at 3.7 kHz and the double zero at 268 Hz
- ❑ Calculate the maximum LED resistor you can accept, apply margin

$$R_{LED,\max} \leq \frac{V_z - V_f - V_{TL431,\min}}{V_{dd} - V_{CE,sat} + I_{bias}\mathrm{CTR}_{\min} R_{pullup}} R_{pullup}\mathrm{CTR}_{\min} \leq 1.5\,k\Omega \xrightarrow{\text{X 0.85}} 1.3\,k\Omega$$

- ❑ We need to account for the extra gain term:

$$G_2 = \frac{R_{pullup}}{R_{LED}}\mathrm{CTR} = \frac{20\mathrm{k}}{1.3\mathrm{k}}0.3 = 4.6$$

- ❑ The required total mid-band <u>attenuation</u> at 1 kHz is -10 dB

$$G_{f_c} = 10^{-10/20} = 0.316$$

TL431 Type 3 Design Example – No Fast Lane

- The mid-band gain from the type 3 is therefore:

$$G_1 = \frac{G_0}{G_2} = \frac{0.316}{4.6} = 0.068 \text{ or } -23.3\, dB$$

- Calculate R_2 for this attenuation:

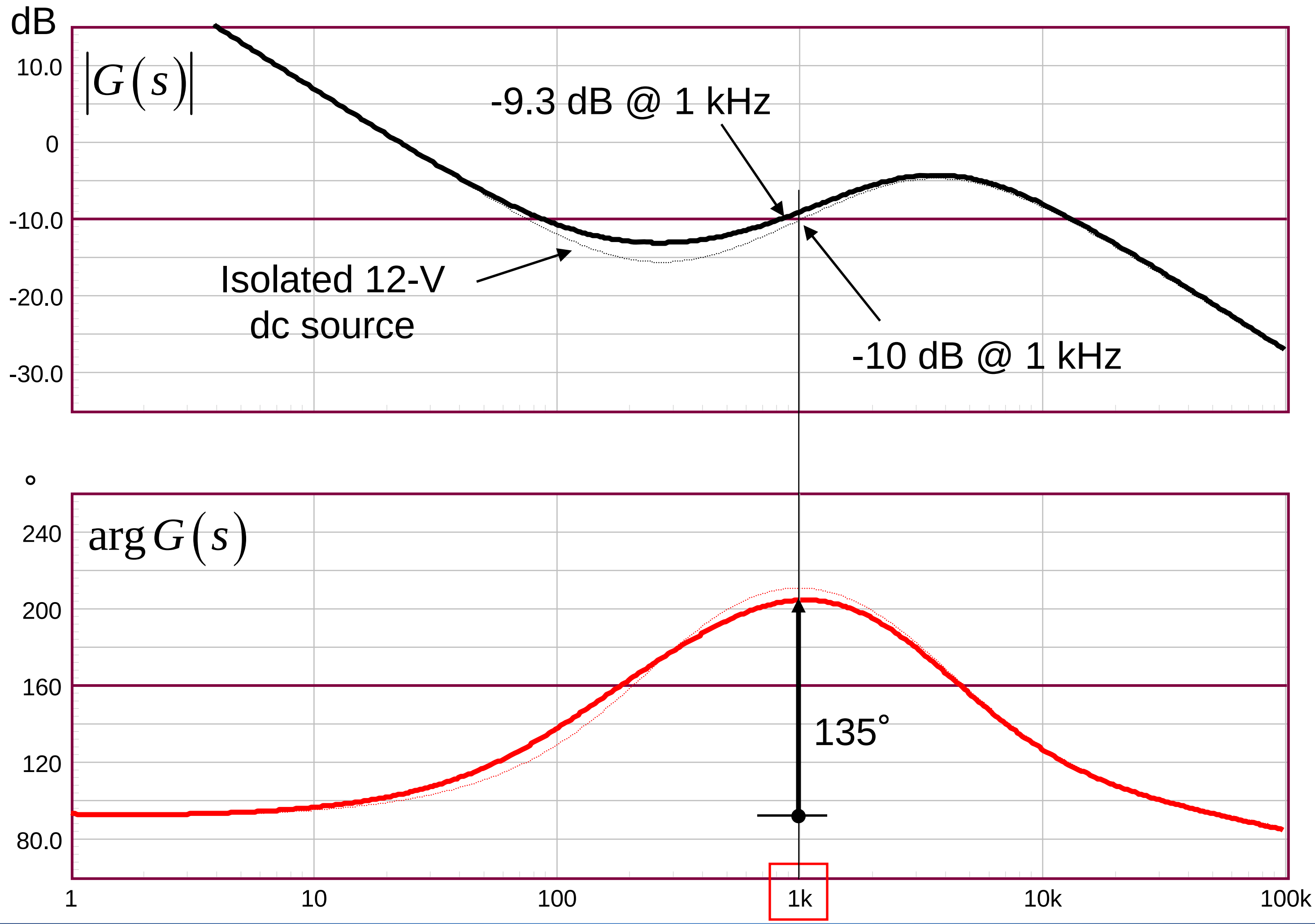
$$R_2 = \frac{G_1 R_1 f_{p_1}}{f_{p_1} - f_{z_1}} \frac{\sqrt{1+\left(\frac{f_c}{f_{p_1}}\right)^2}\sqrt{1+\left(\frac{f_c}{f_{p_2}}\right)^2}}{\sqrt{1+\left(\frac{f_{z_1}}{f_c}\right)^2}\sqrt{1+\left(\frac{f_c}{f_{z_2}}\right)^2}} = 744\,\Omega$$

$$C_1 = 800\, nF \;\; C_2 = 148\, pF \;\; C_3 = 14.5\, nF \;\; C_{opto} = 2\, nF$$

- The optocoupler pole limits the upper double pole position
- The maximum boost therefore depends on the crossover frequency

TL431 Type 3 Design Example – No Fast Lane

- The decoupling between V_{out} and V_{bias} affects the curves

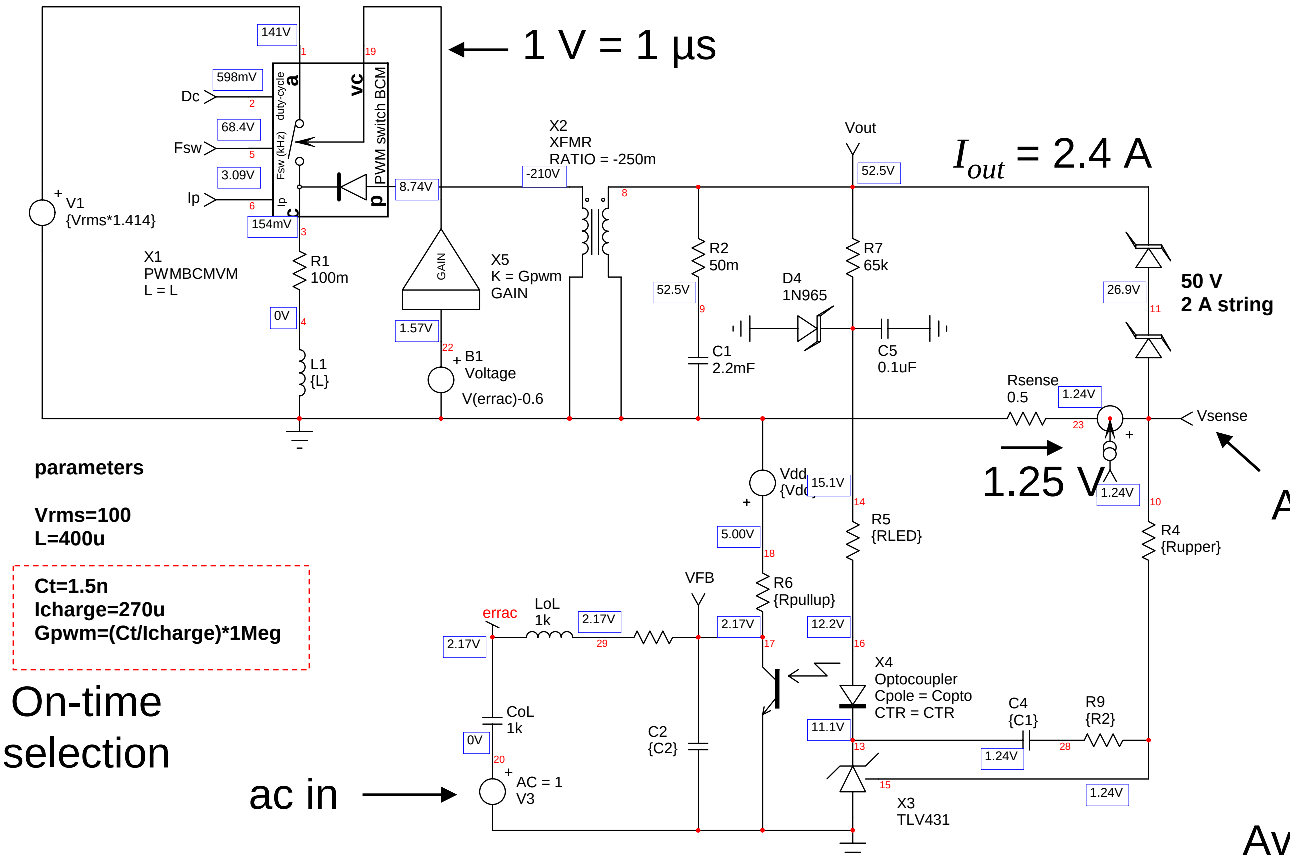


Agenda

- ❑ Feedback generalities
- ❑ The TL431 in a compensator
- ❑ Small-signal analysis of the return chain
- ❑ A type 1 implementation with the TL431
- ❑ A type 2 implementation with the TL431
- ❑ A type 3 implementation with the TL431
- ❑ **Design examples**
- ❑ Conclusion

Design Example 1 – a Single-Stage PFC

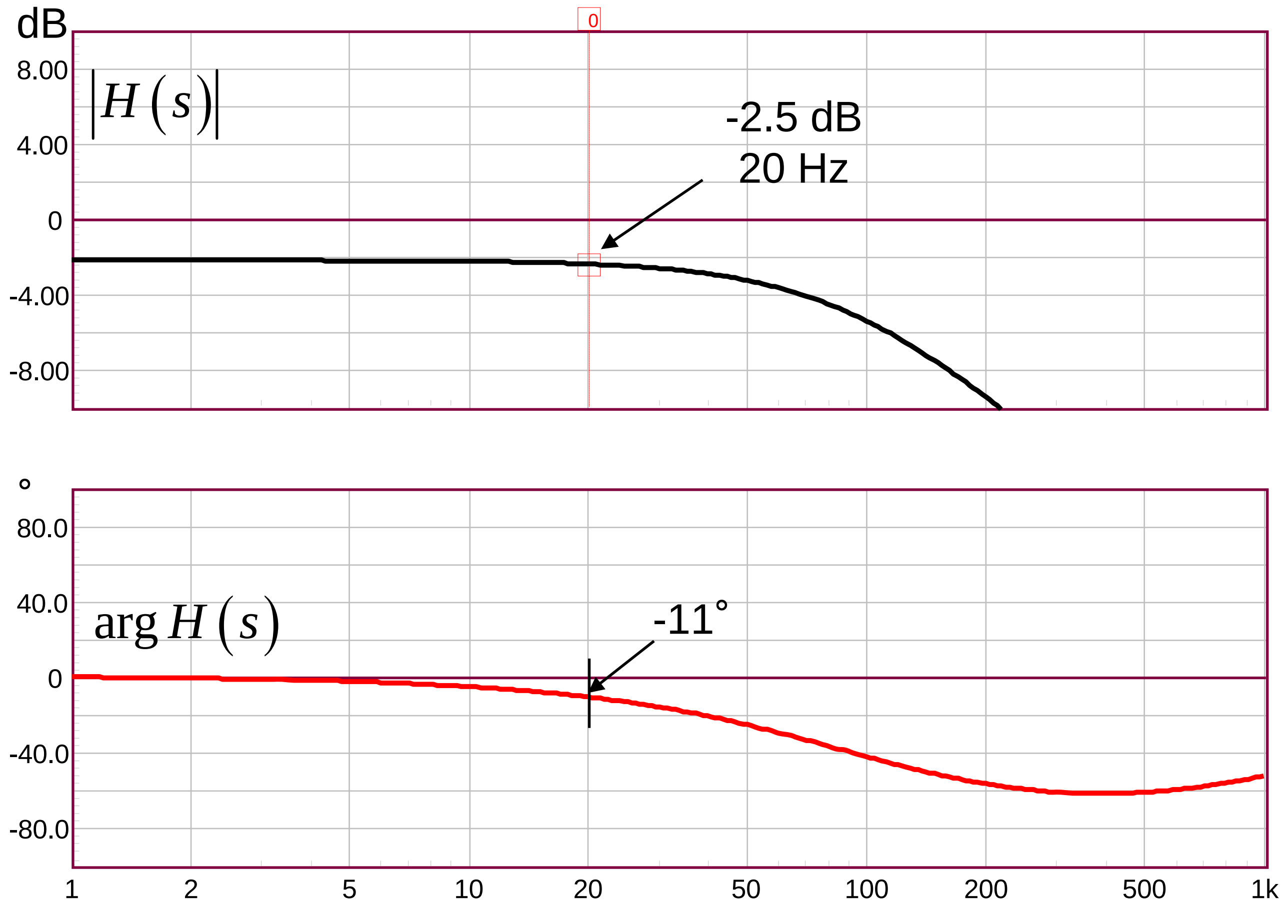
- The single-stage PFC is often used in LED applications
- It combines isolation, current-regulation and power factor correction
- Here, a constant on-time BCM controller, the ***NCL30000***, is used



Average simulation

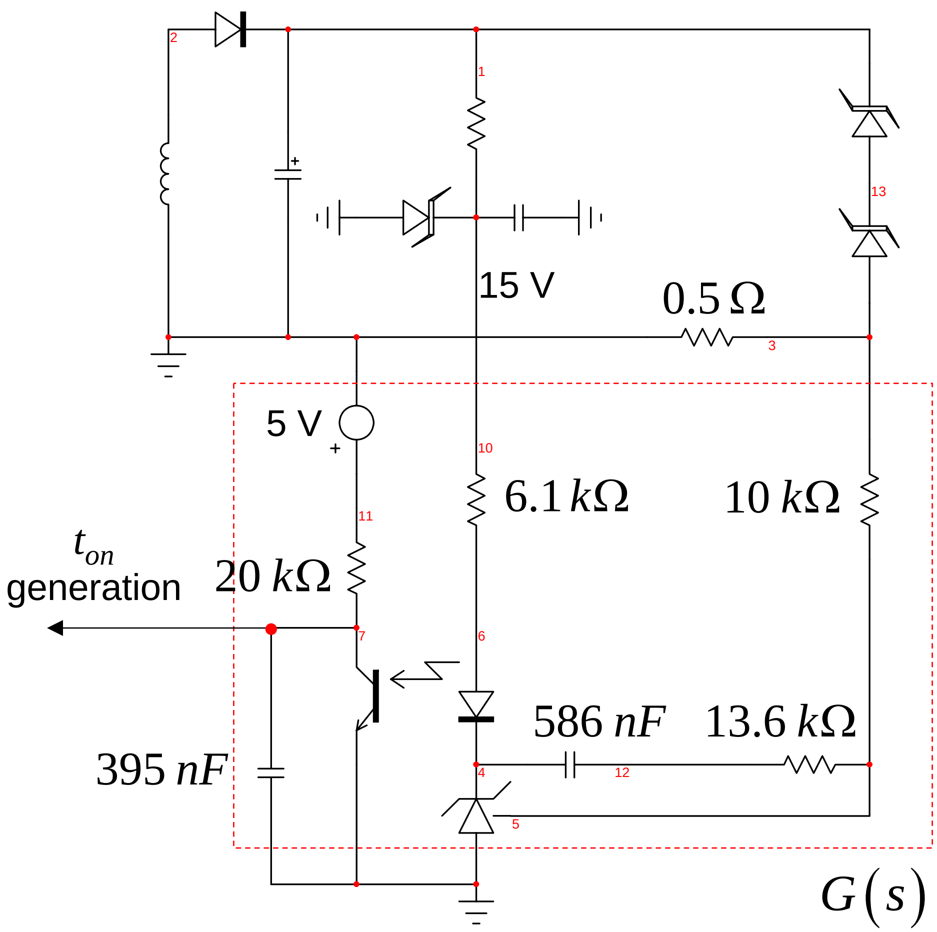
Design Example 1 – a Single-Stage PFC

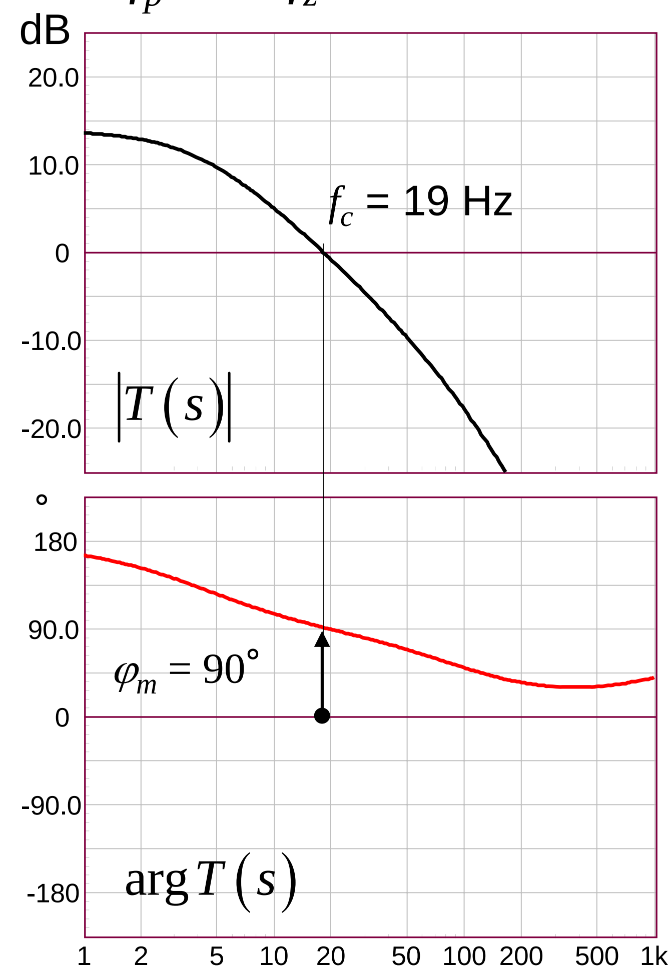
- Once the converter elements are known, ac-sweep the circuit
- Select a crossover low enough to reject the ripple, e.g. 20 Hz



Design Example 1 – a Single-Stage PFC

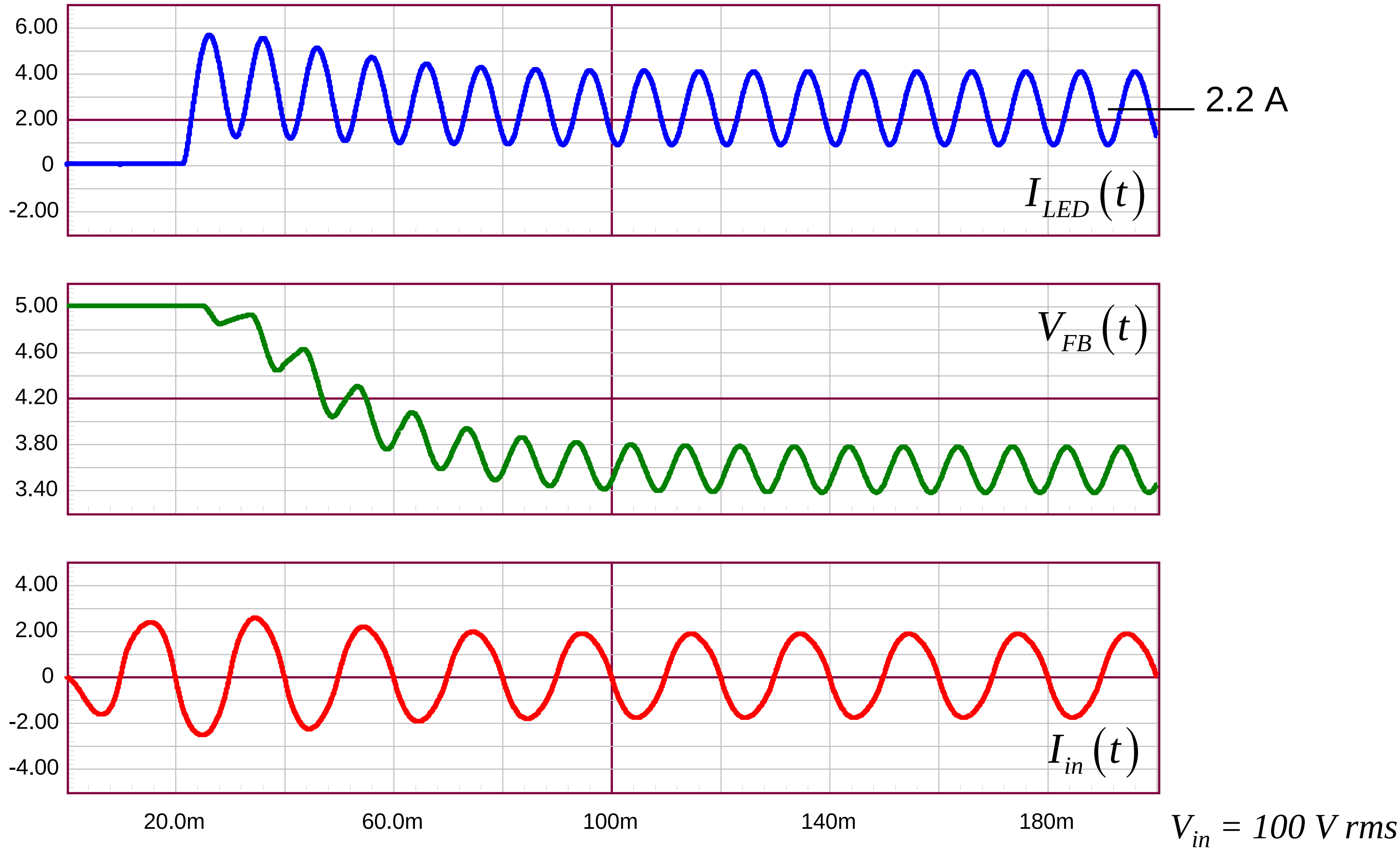
- ❑ Given the low phase lag, a type 1 can be chosen
- ➢ Use the type 2 with fast lane removal where f_p and f_z are coincident





Design Example 1 – a Single-Stage PFC

❑ A transient simulation helps to test the system stability



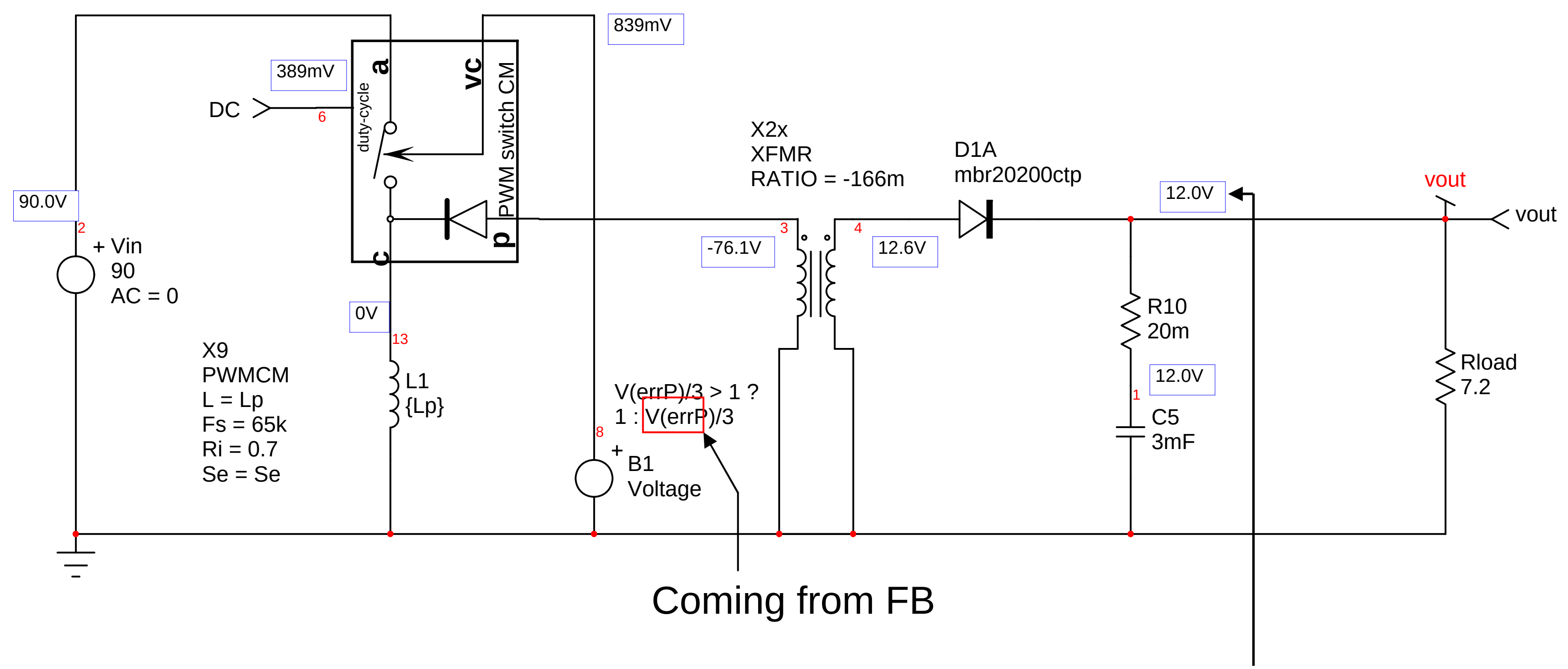
Design Example 2: a DCM Flyback Converter

- We want to stabilize a 20 W DCM adapter
- V_{in} = 85 to 265 V rms, V_{out} = 12 V/1.7 A
- F_{sw} = 65 kHz, R_{pullup} = 20 kΩ
- Optocoupler is SFH-615A, pole is at 6 kHz
- Cross over target is 1 kHz
- Selected controller: NCP1216

1. Obtain a power stage open-loop Bode plot, $H(s)$
2. Look for gain and phase values at cross over
3. Compensate gain and build phase at cross over, $G(s)$
4. Run a loop gain analysis to check for margins, $T(s)$
5. Test transient responses in various conditions

Design Example 2: a DCM Flyback Converter

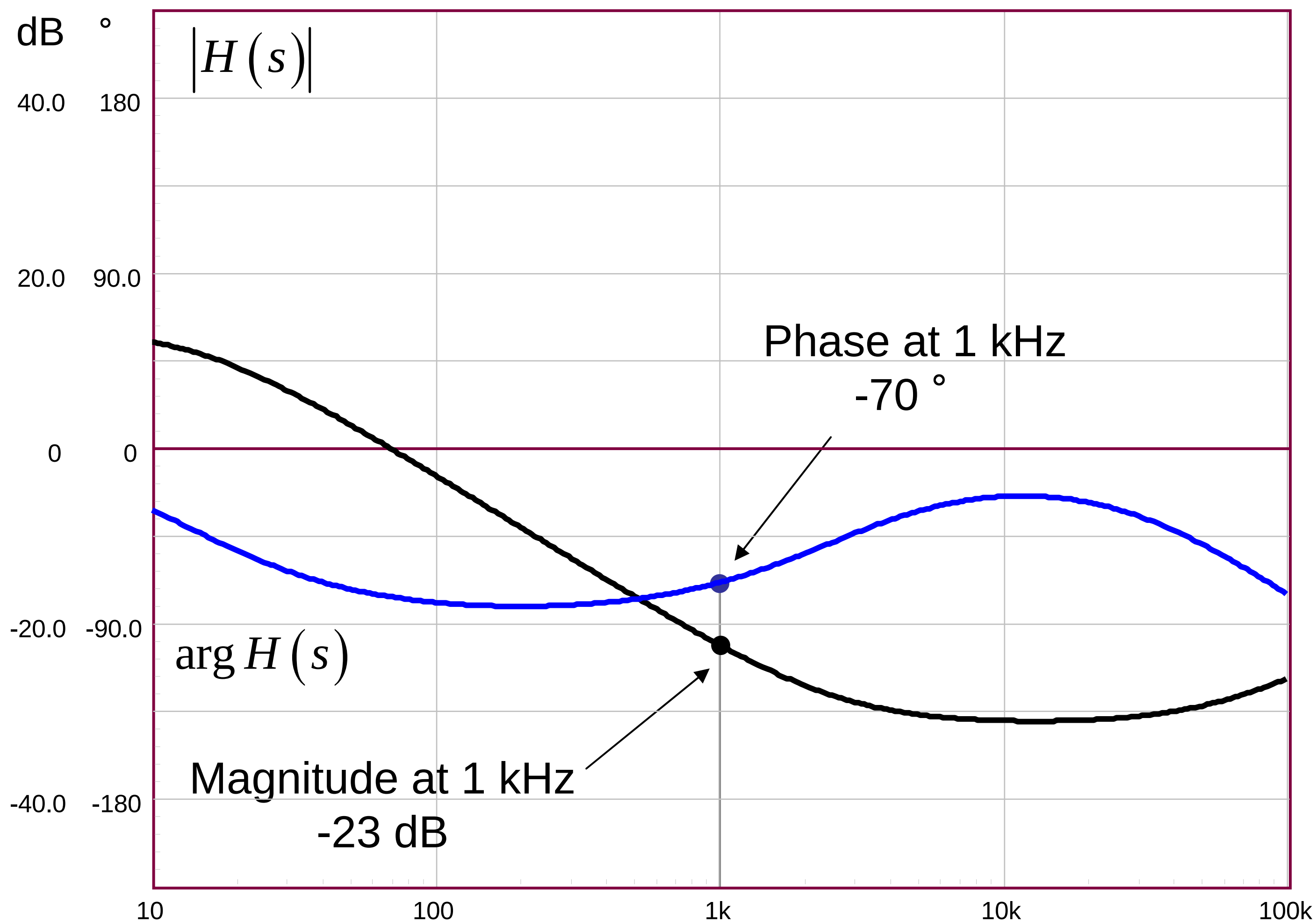
❑ Capture a SPICE schematic with an averaged model



❑ Look for the bias points values: V_{out} = 12 V, ok

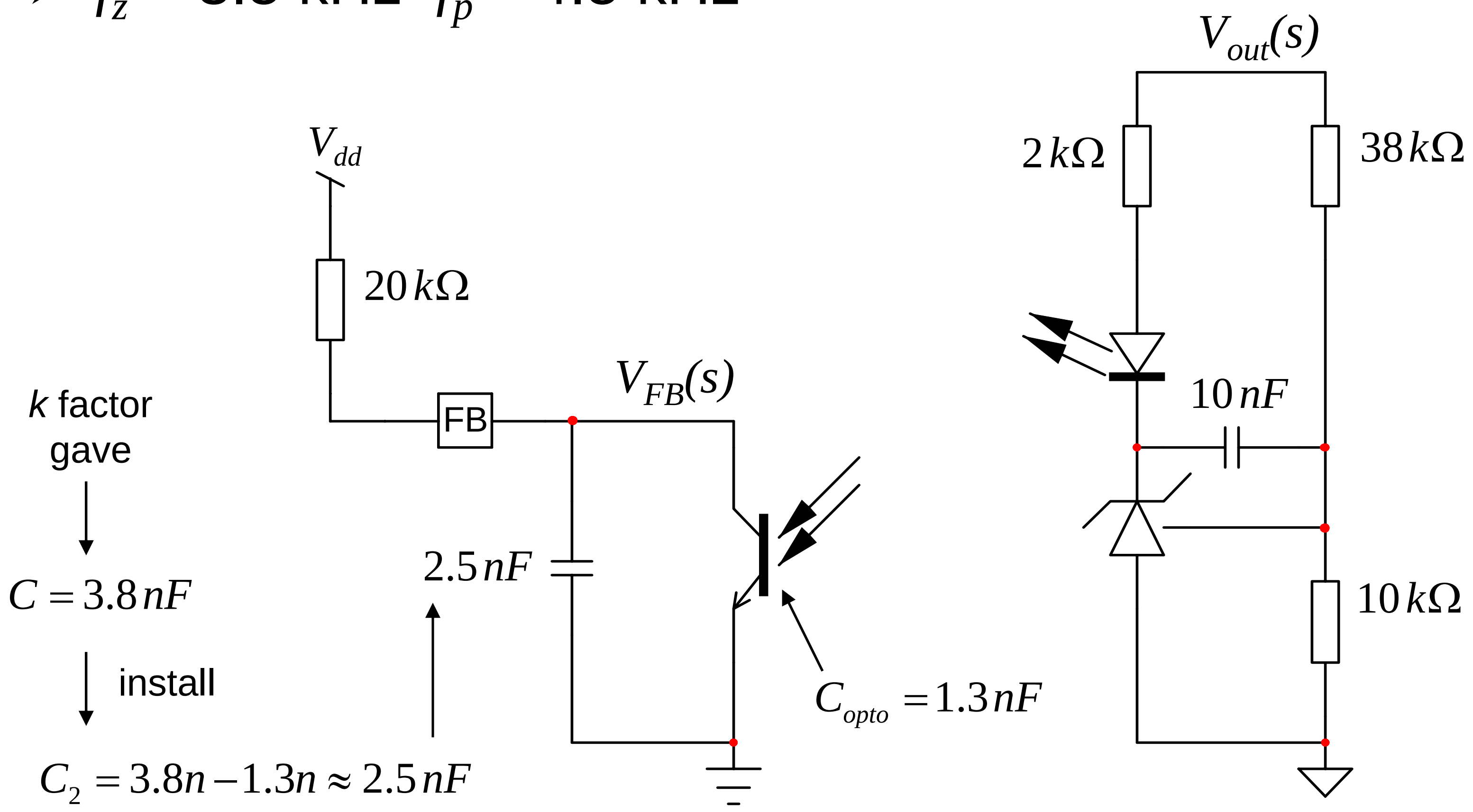
Design Example 2: a DCM Flyback Converter

- Observe the open-loop Bode plot and select f_c: 1 kHz



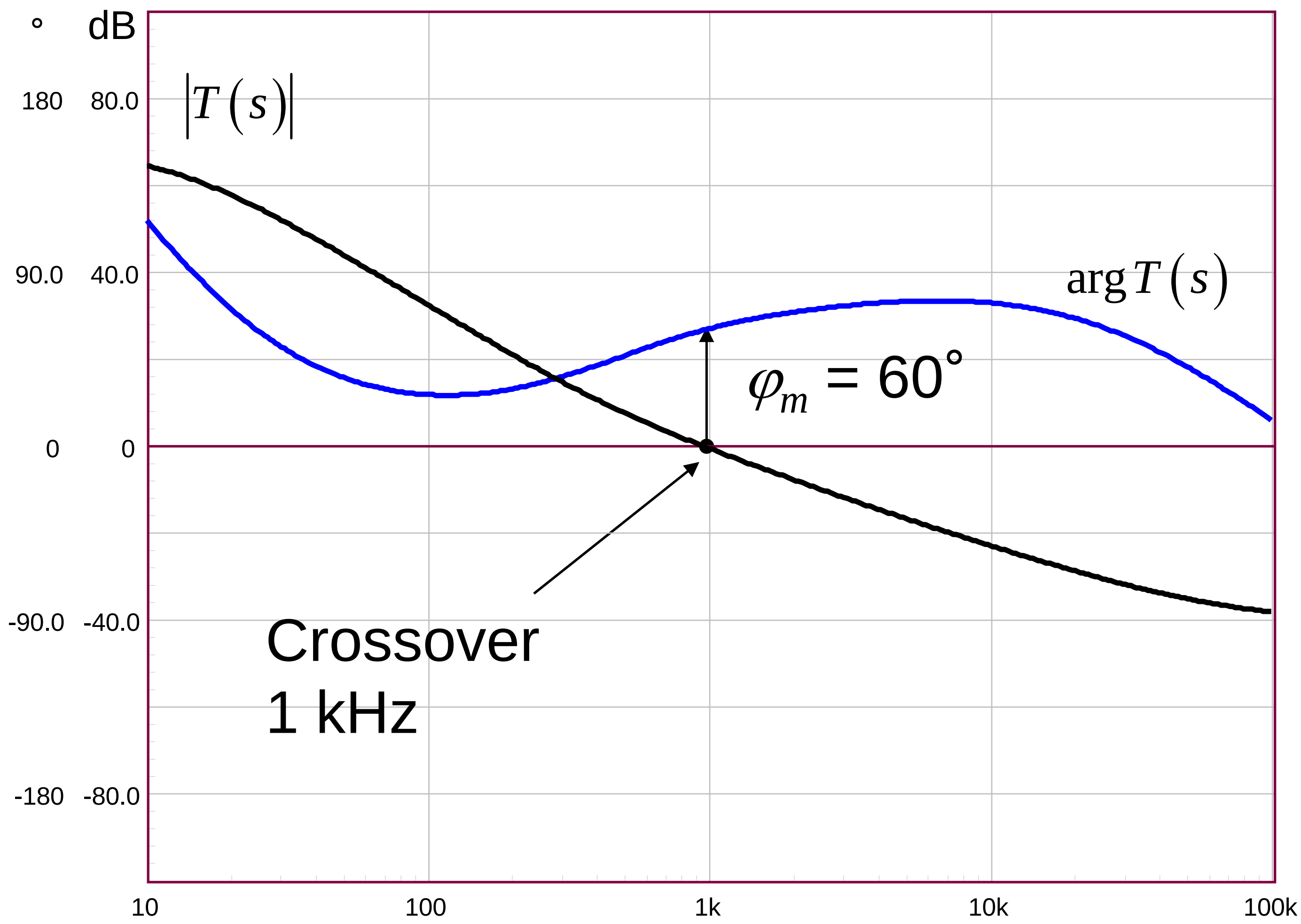
Design Example 2: a DCM Flyback Converter

- ❑ Apply *k* factor or other method, get f_z and f_p
  - ➢ f_z = 3.5 kHz f_p = 4.5 kHz



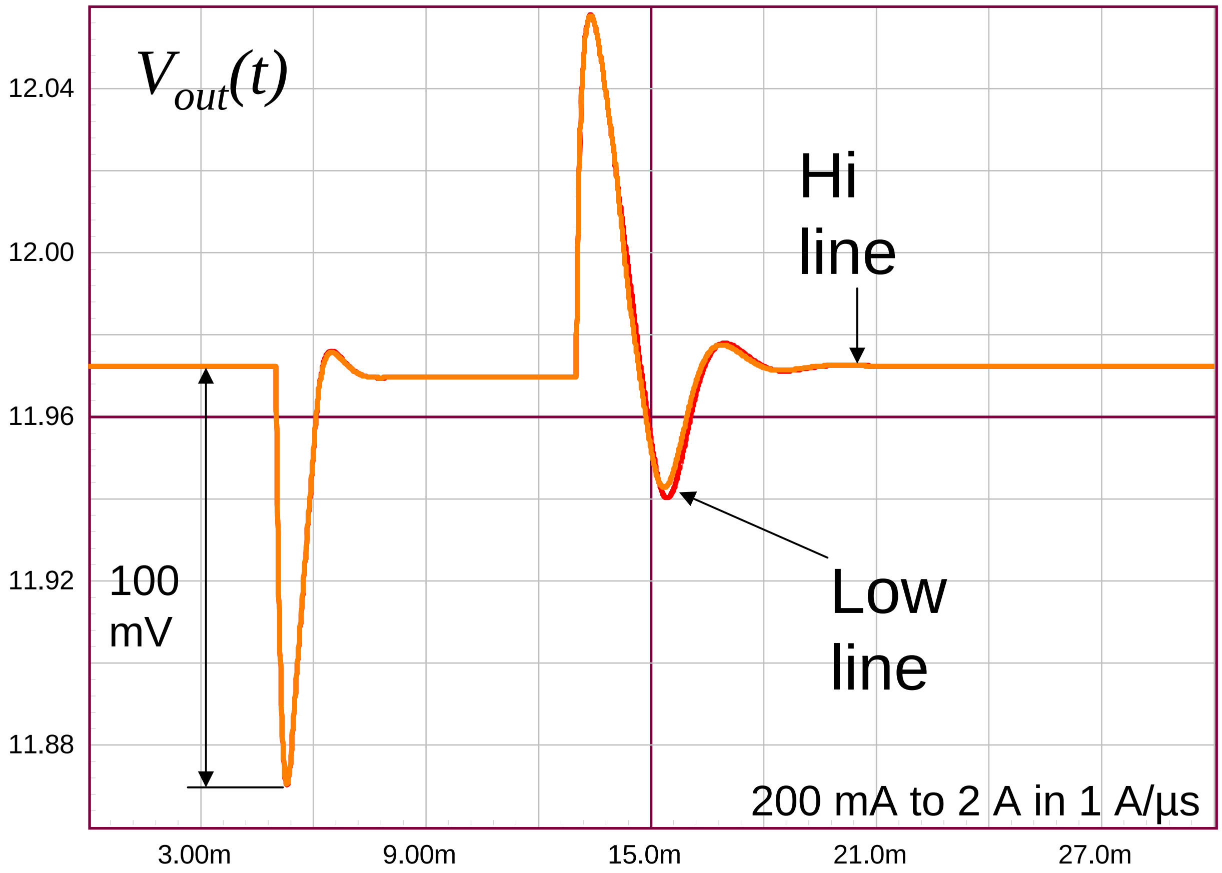
Design Example 2: a DCM Flyback Converter

- Check loop gain and watch phase margin at f_c



Design Example 2: a DCM Flyback Converter

- ❑ Sweep ESR values and check margins again



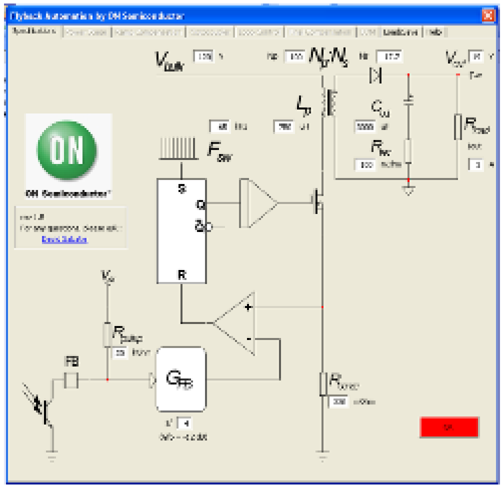
Excellent!

Use an Automated Design Tool

- To speed-up your design studies, use the right tool!

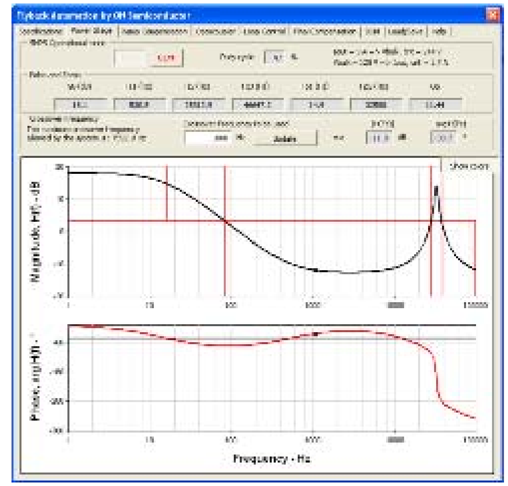
1.

Enter calculated values



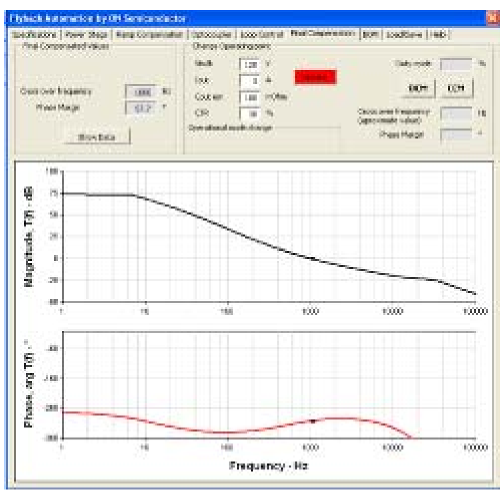
2.

Show power stage gain and phase



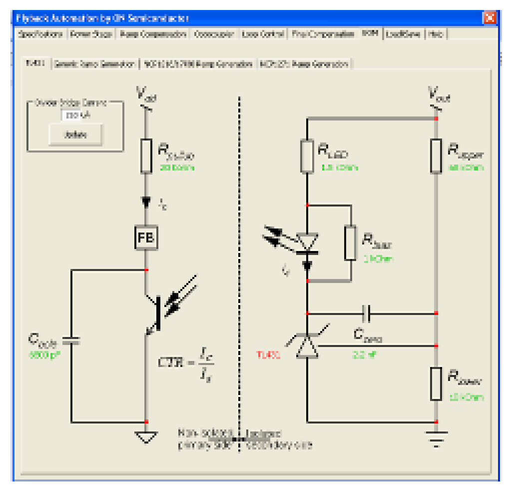
3.

Compute pole/zero check open loop gain



4.

See final values on TL431



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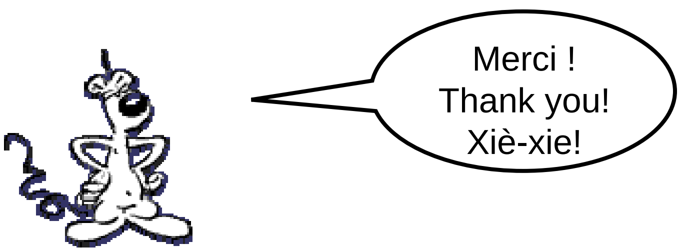
Conclusion

- ❑ Classical loop control theory describes op amps in compensators
- ❑ Engineers cannot apply their knowledge to the TL431
- ❑ Examples show that the TL431 with an optocoupler have limits
- ❑ Once these limits are understood, the TL431 is simple to use
- ❑ All three compensator types have been covered
- ❑ Design examples showed the power of averaged models
- ❑ Use them to extensively reproduce parameter dispersions
- ❑ Applying these recipes is key to design success!



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- View reference designs, design notes, and other material supporting the design of highly efficient power supplies at www.onsemi.com/powersupplies