INSTITUT d'OPTIQUE GRADUATE SCHOOL ParisTech
LEnsE
Laboratoire d'Enseignement Expérimental

Bases de photodétection

Opto-Electronique / Semestre 5
Institut d'Optique

Julien VILLEMEJANE

INSTITUT d'OPTIQUE GRADUATE SCHOOL ParisTech | LEnsE Laboratoire d'Enseignement Expérimental

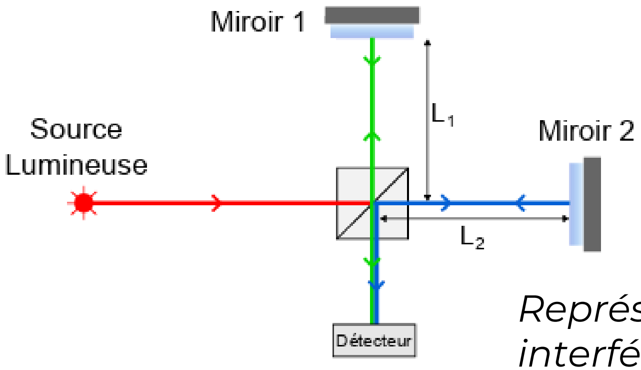
Photodétection

Exemples

Opto-Electronique / Semestre 5
Institut d'Optique

Julien VILLEMEJANE

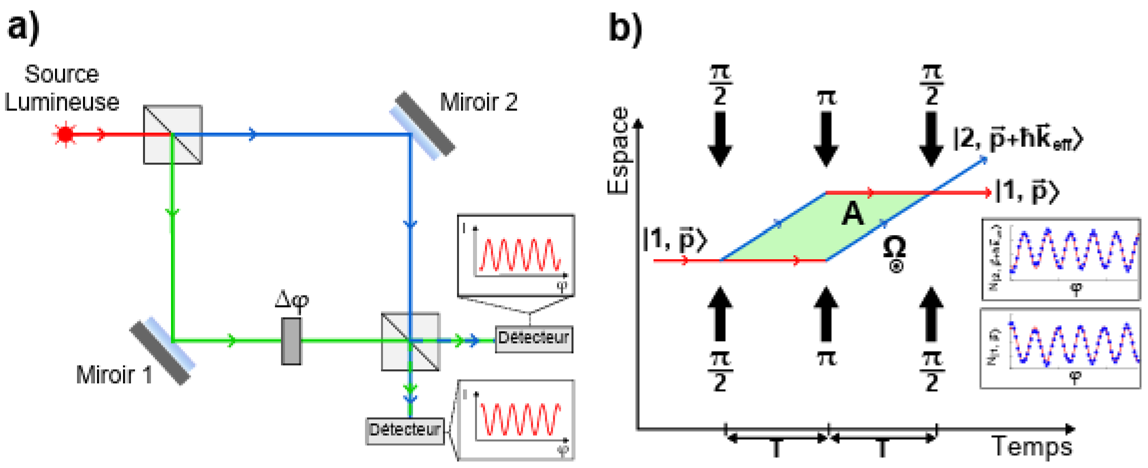
Quelques utilisations des photodiodes



*Représentation d'un interféromètre de **Michelson***

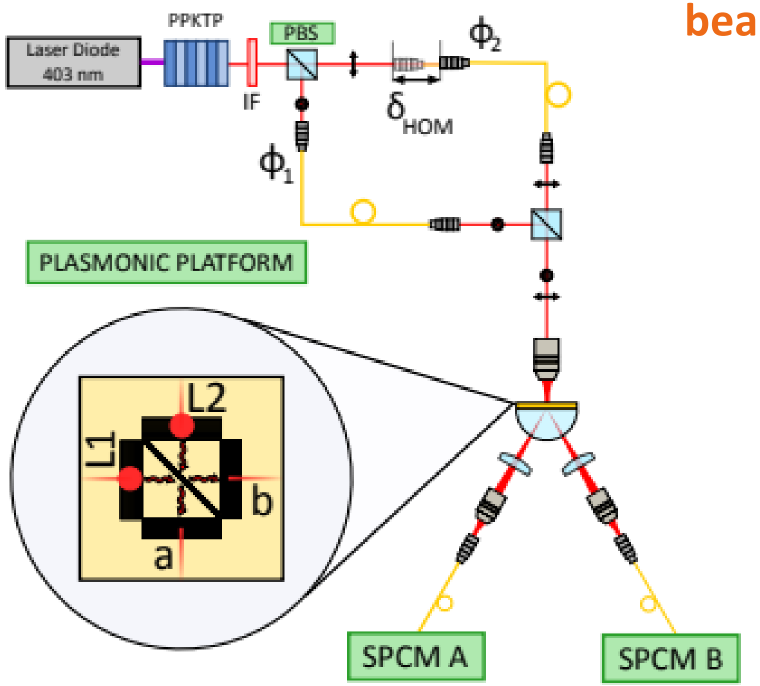
Interféromètre à atomes froids piégés sur puce avec séparation spatiale

Groupe Gaz Quantiques / LCF



*Représentation d'un interféromètre de **Mach-Zehnder** (a) en optique, et (b) en version atomique, aussi appelé Ramsey-Bordé.*

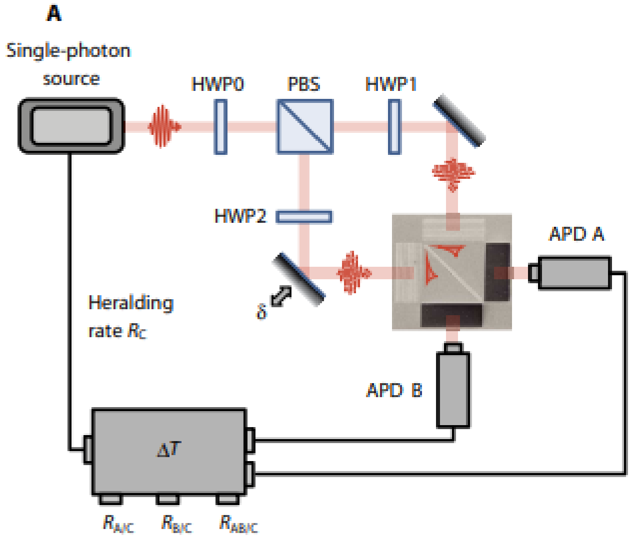
Quelques utilisations des photodiodes



Anti-coalescence of bosons on a lossy beamsplitter

Groupe Nanophotonique / LCF

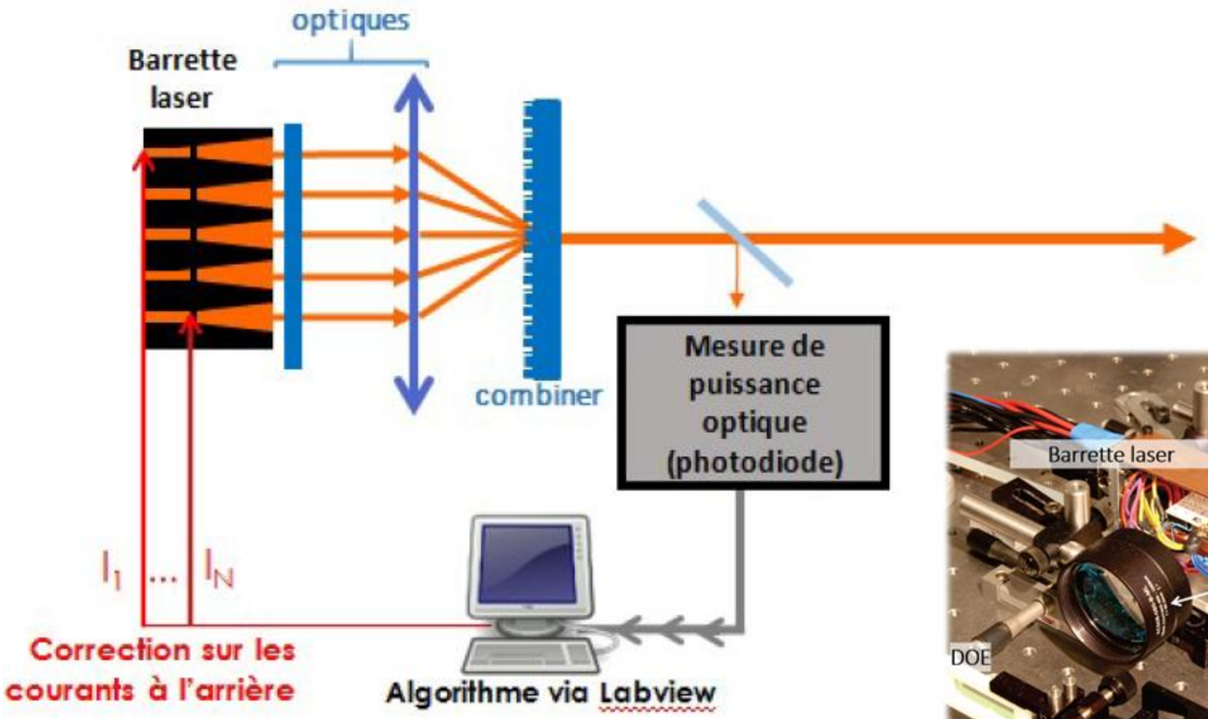
Single-plasmon interferences

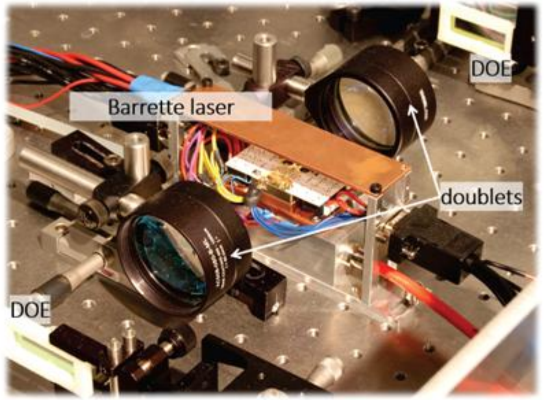


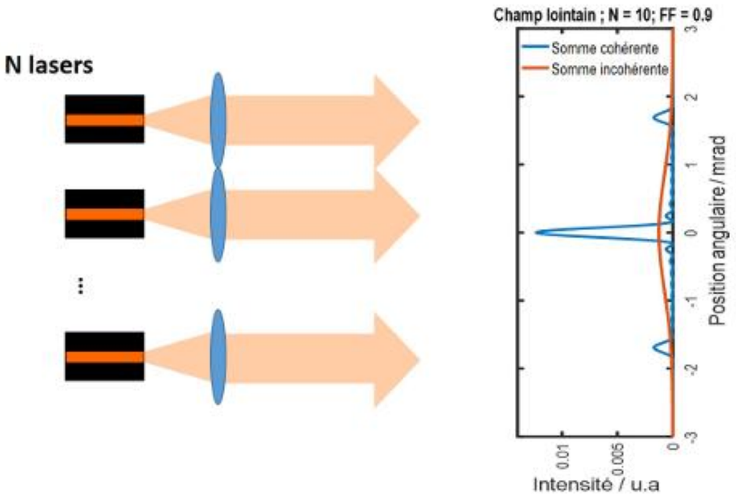
Quelques utilisations des photodiodes

Combinaison cohérente de diodes laser de puissance

Groupe Laser / LCF







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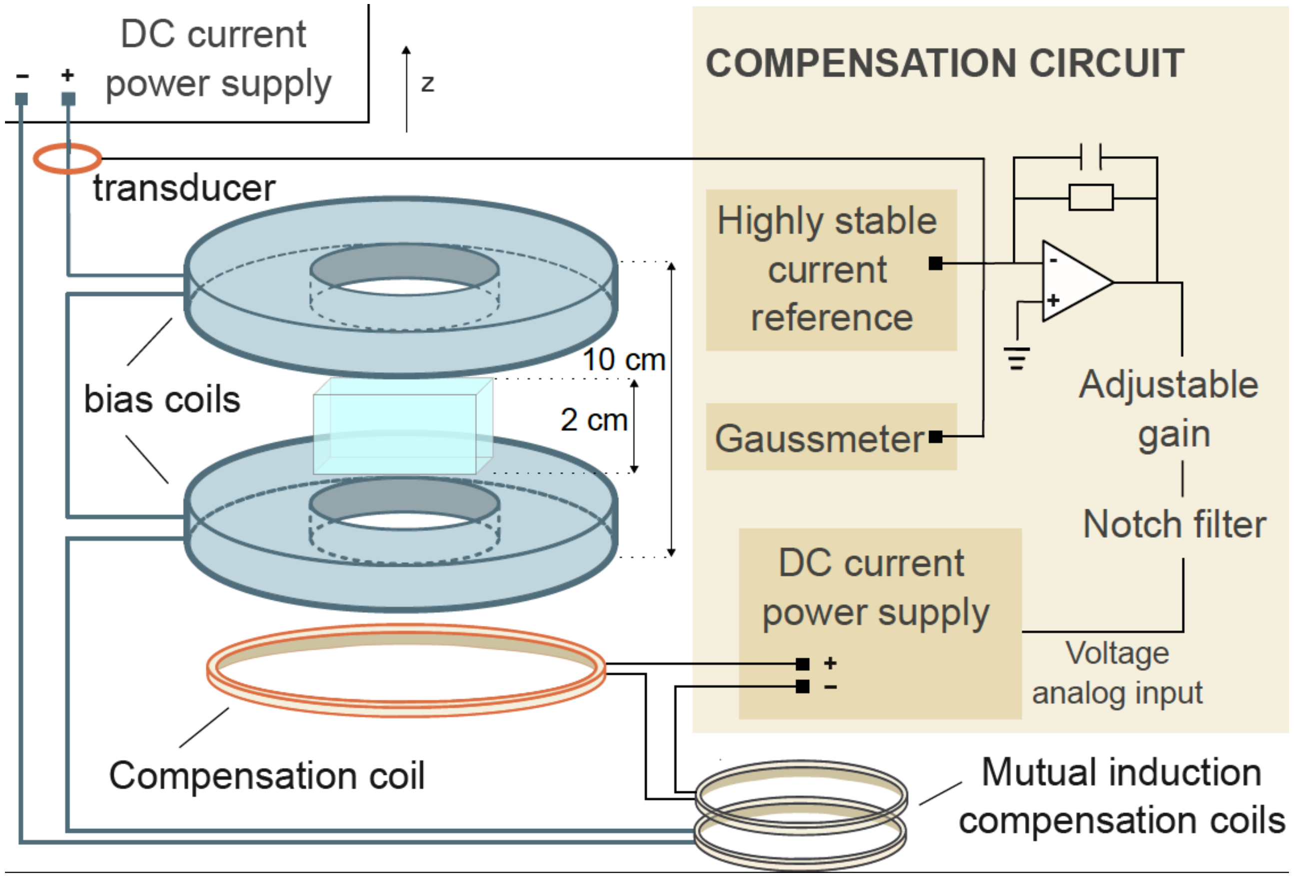
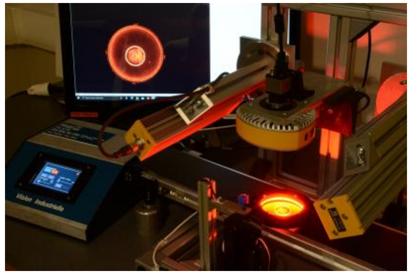


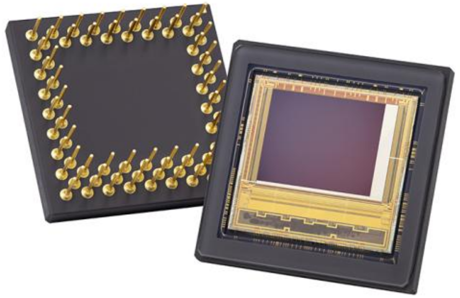
Magnetic field stabilisation for Bose-Einstein condensation experiments

Groupe Gaz Quantique / LCF

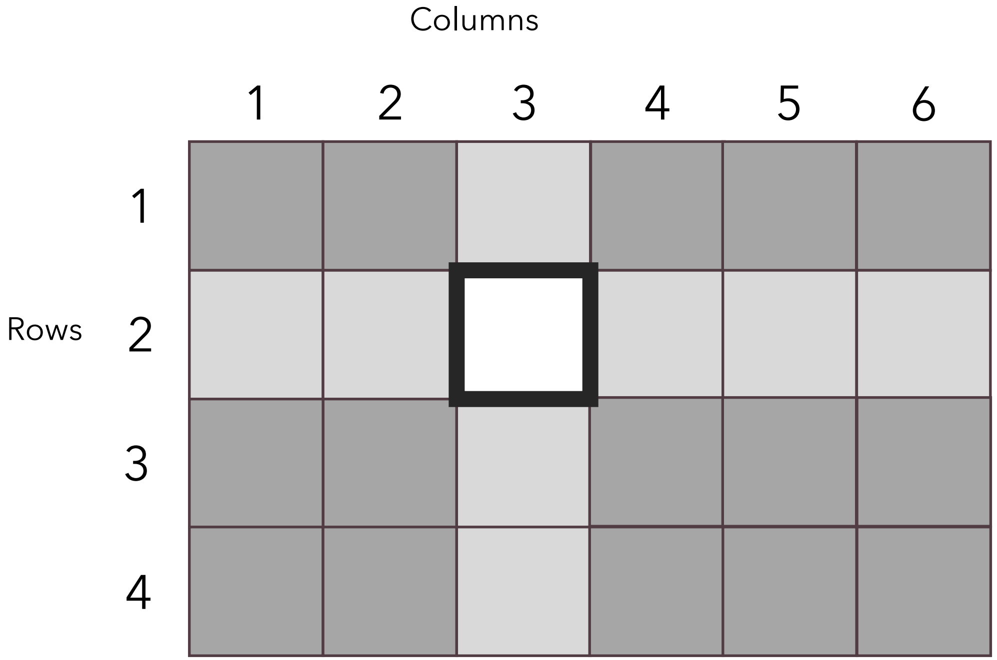
*Schematic of the **stabilization system**. In essence, it is a **feedforward** technique in a separated coil. A key feature is that the mutual inductance between the two circuits is cancelled.*



Camera / Array of small sensors

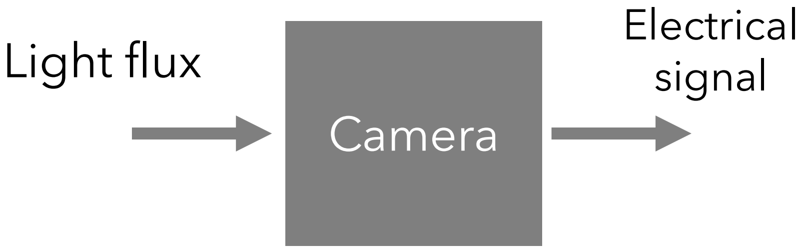


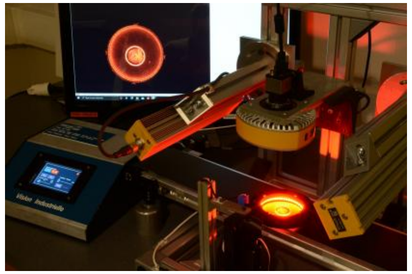
https://imaging.teledyne-e2v.com/products/2d-cmos-image-sensors/onyxmax/



Camera

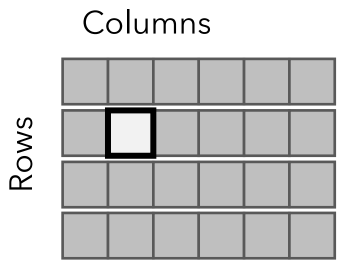
Device that transforms a **light flux** into a **measurable electrical signal**

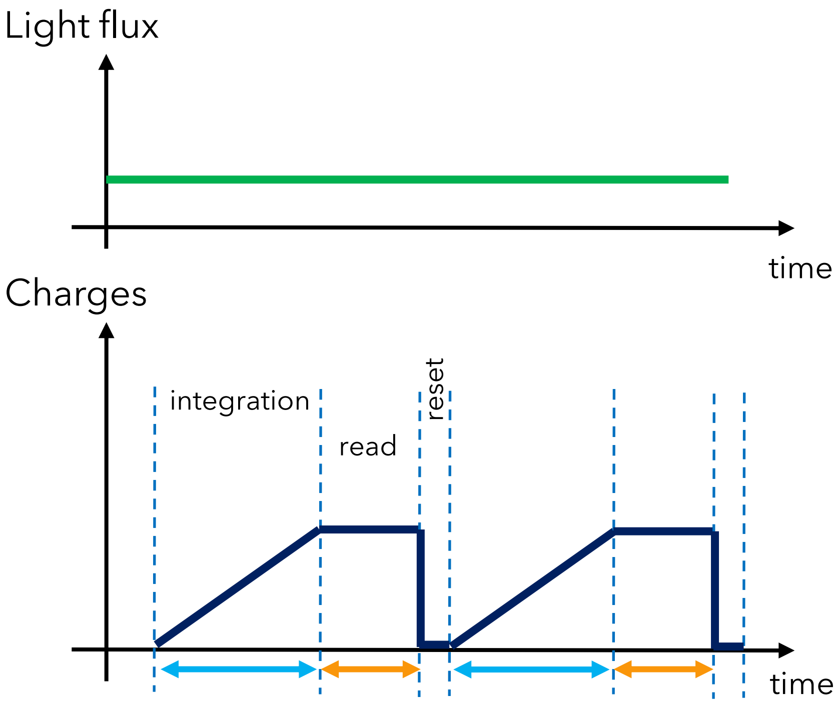




SC19 – Cameras and Interfaces

Exposure Time



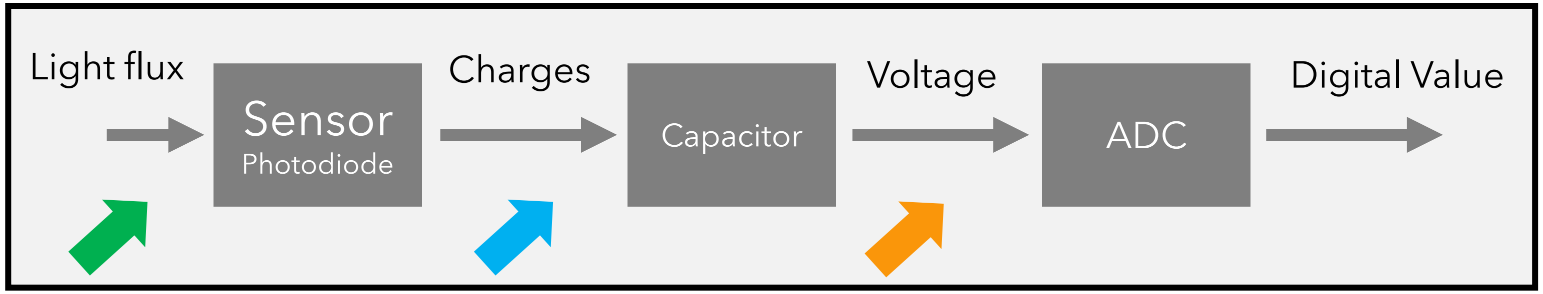


Exposure Time

Duration for which the **camera's sensor is exposed to light**, when capturing an image.

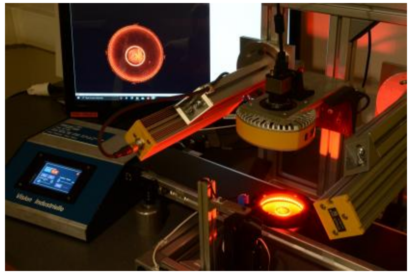
This parameter determines the amount of light collected.

i.e. the amount of collected charges coming from the sensor stored in a capacitor



Continuing Education

Formation Continue



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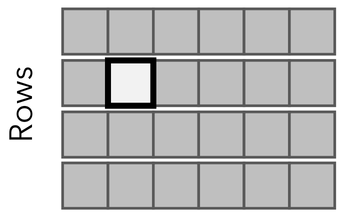

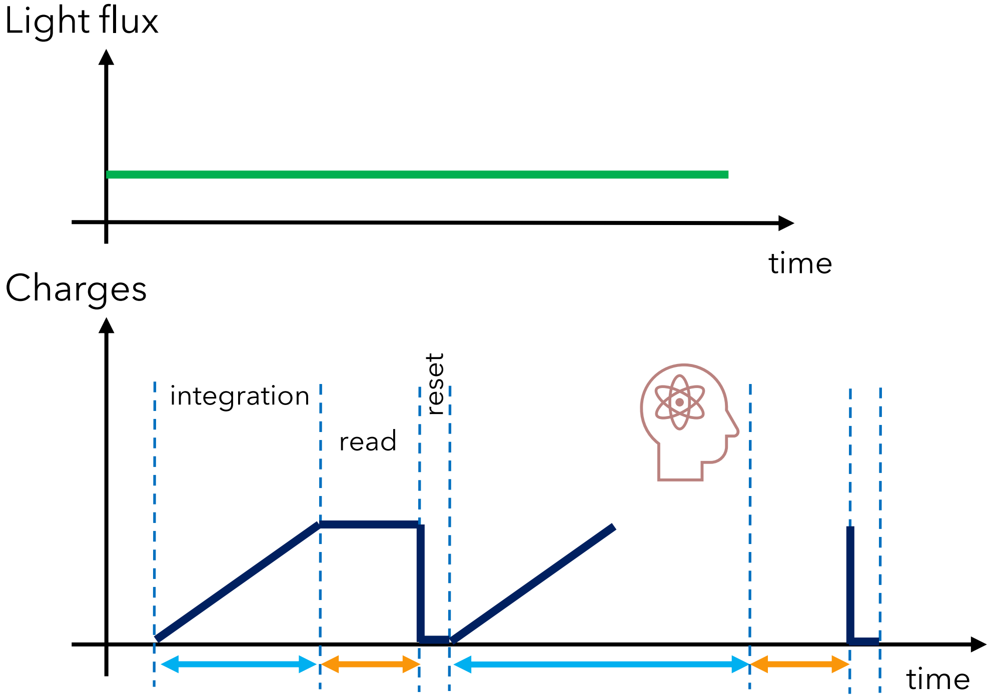

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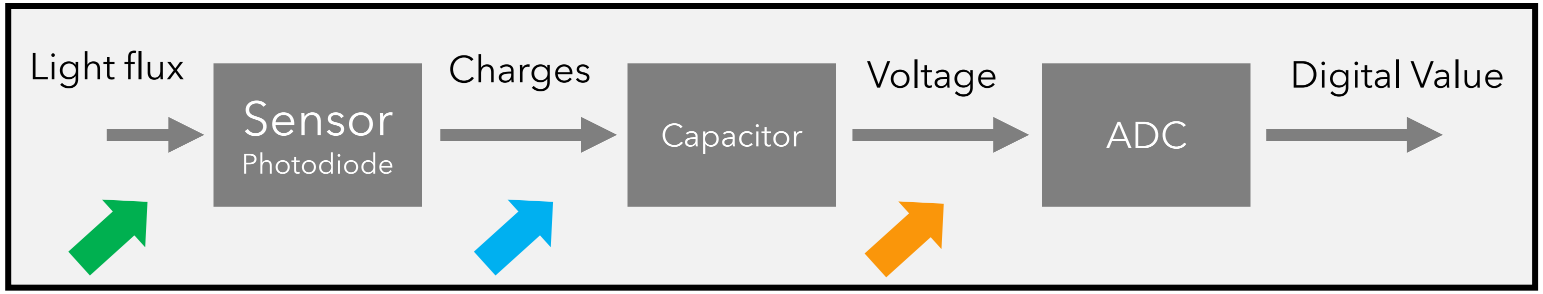

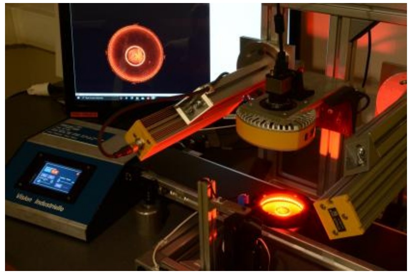

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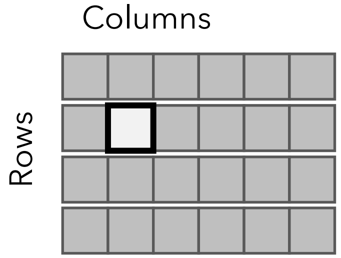

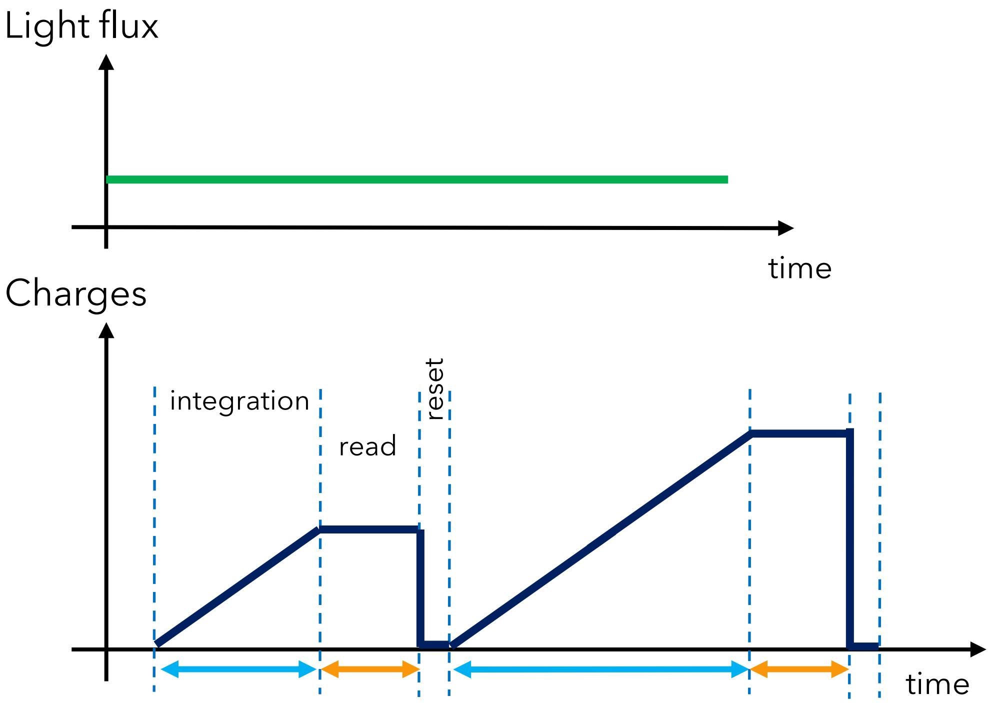

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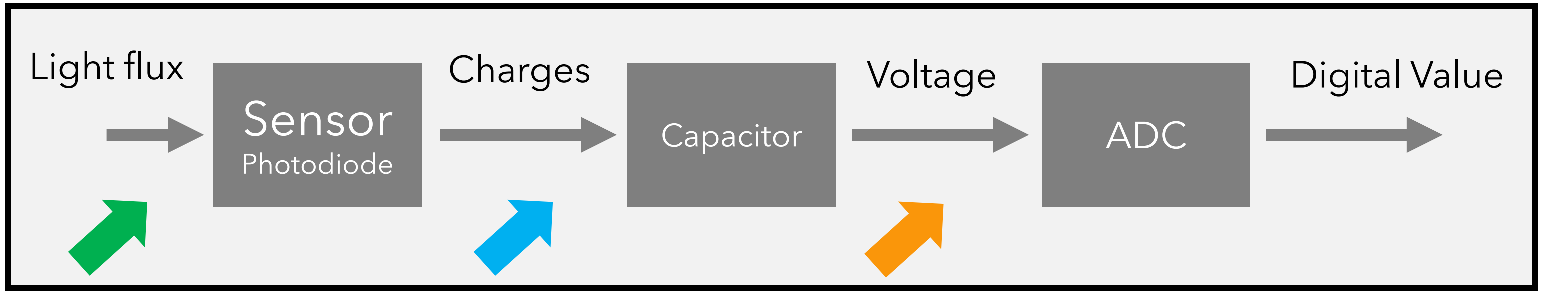
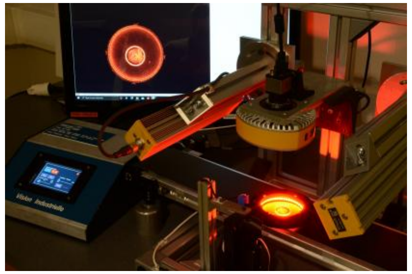


Continuing Education

Formation Continue



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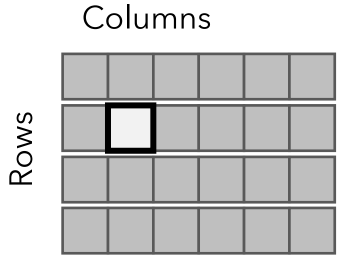

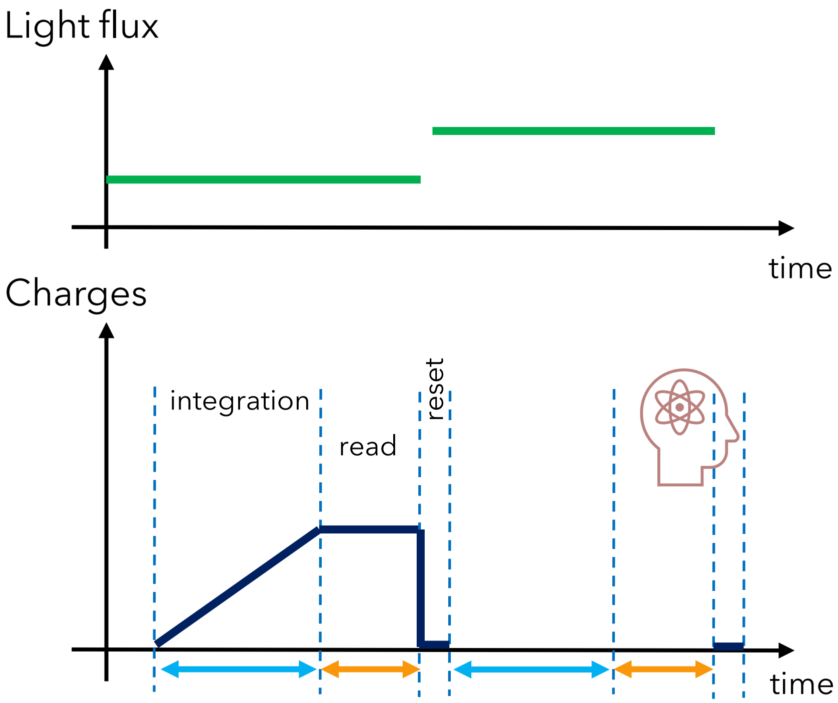

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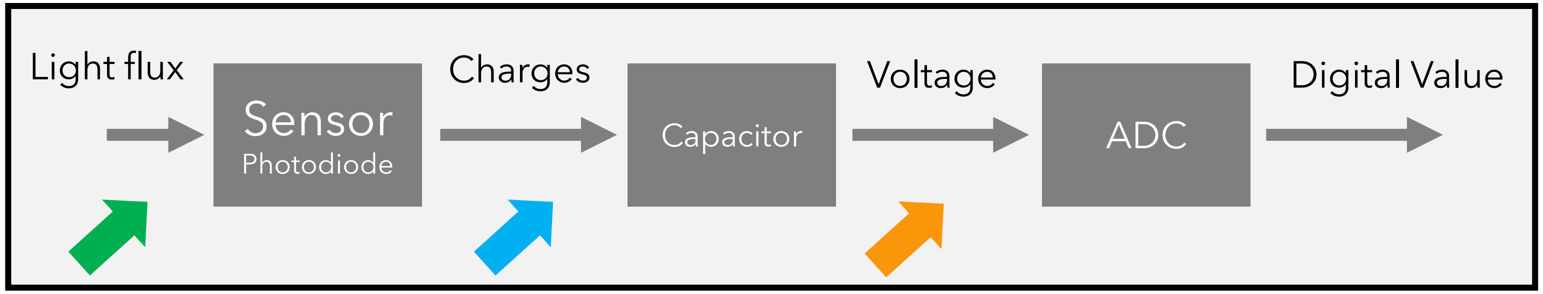
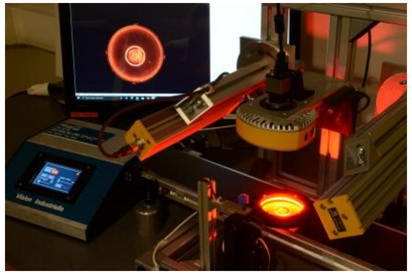


Continuing Education

Formation Continue



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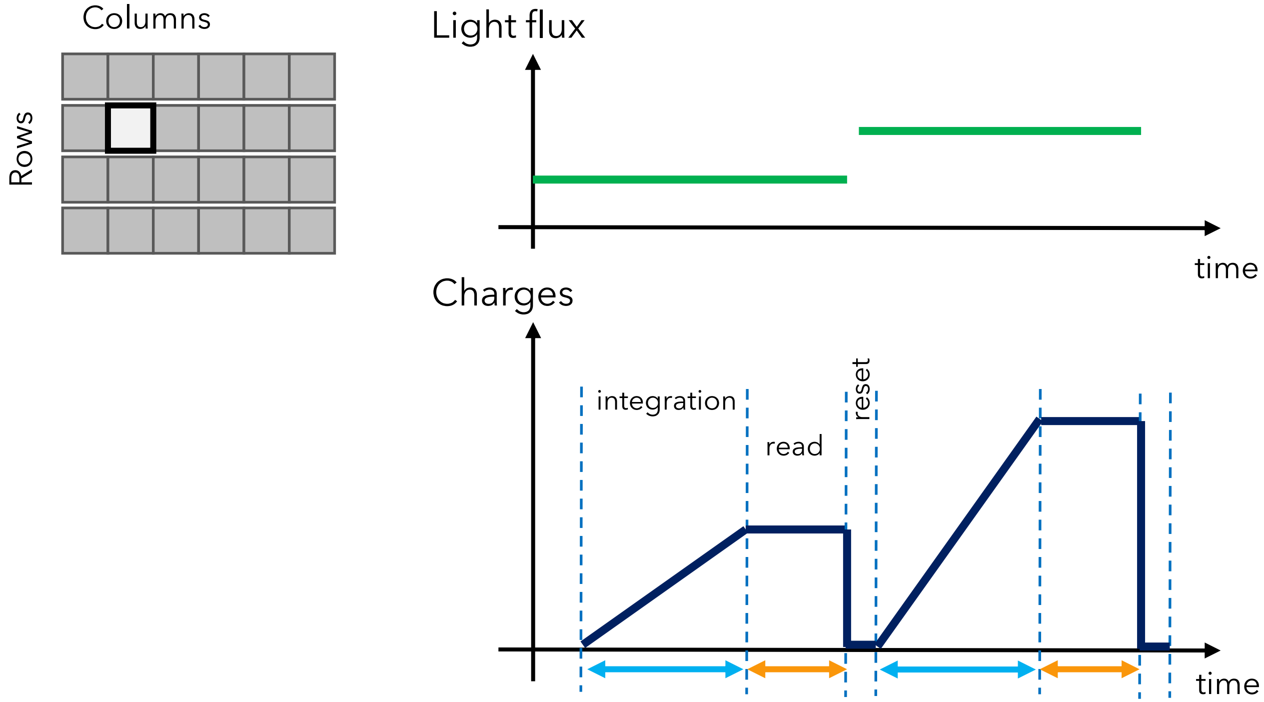

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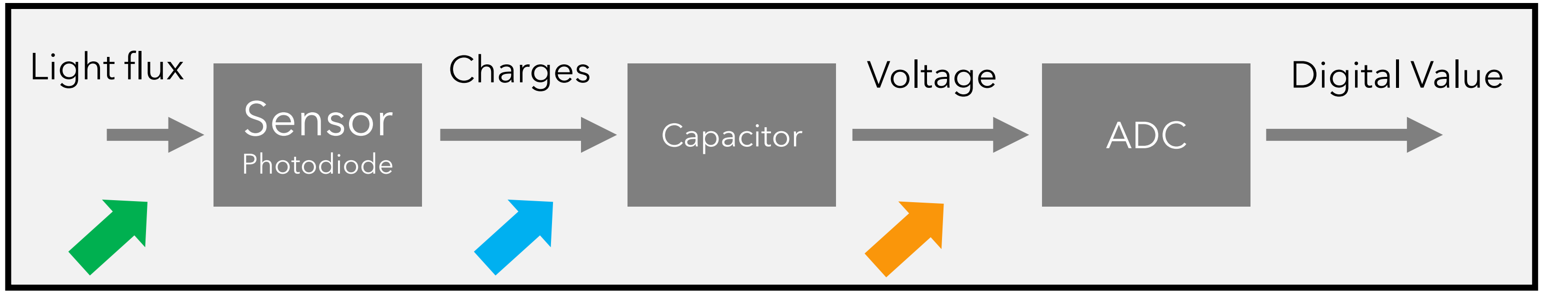

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LEDs

Opto-Electronique / Semestre 5
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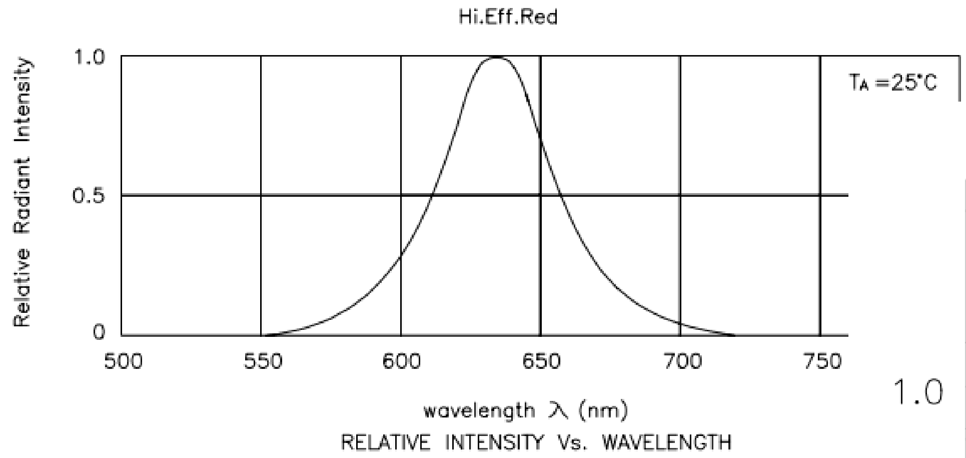
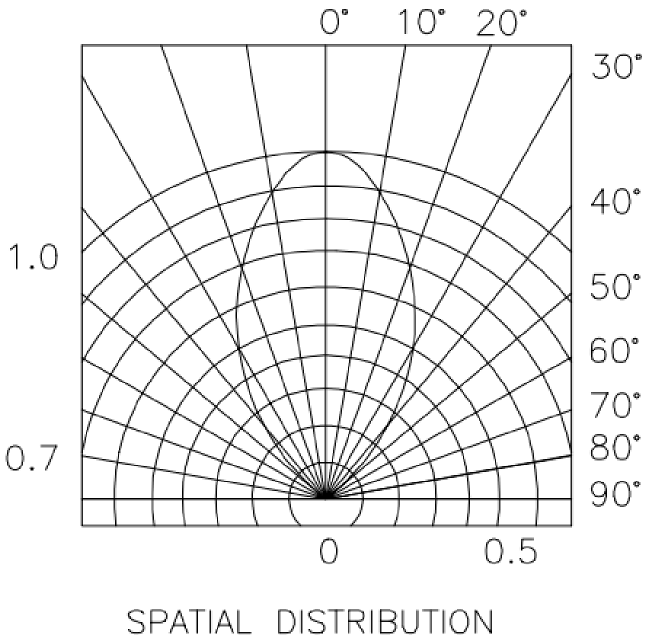
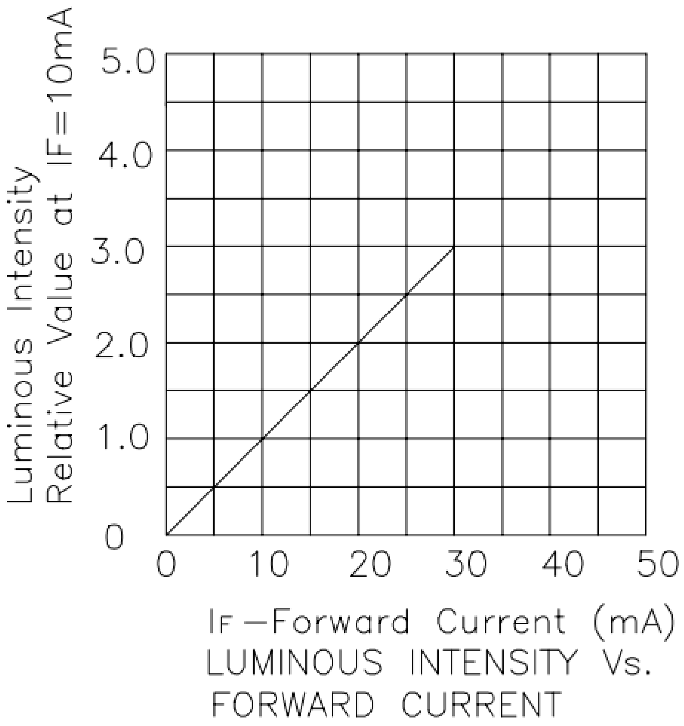
LEDs et circuits d'émission





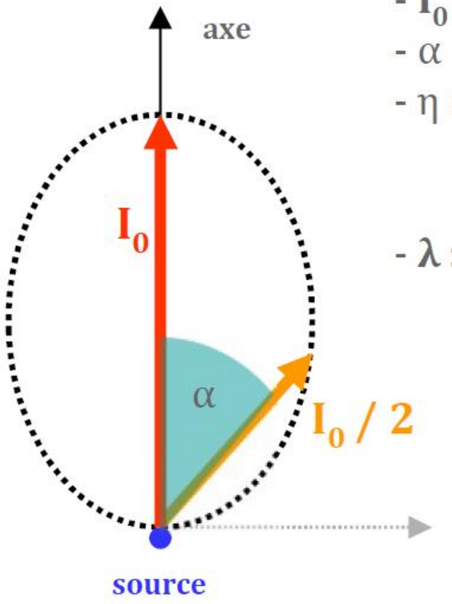


Source de photons

Kingbright **High Efficiency Red** **L-53ID**

LEDs et circuits d'émission

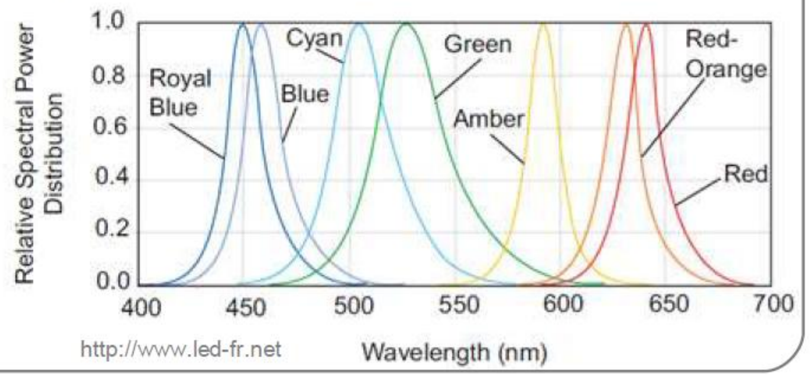
CARACTÉRISTIQUES OPTIQUES



- I_0 : intensité lumineuse sur l'axe
- α : demi-angle (directivité)
- η : rendement de conversion

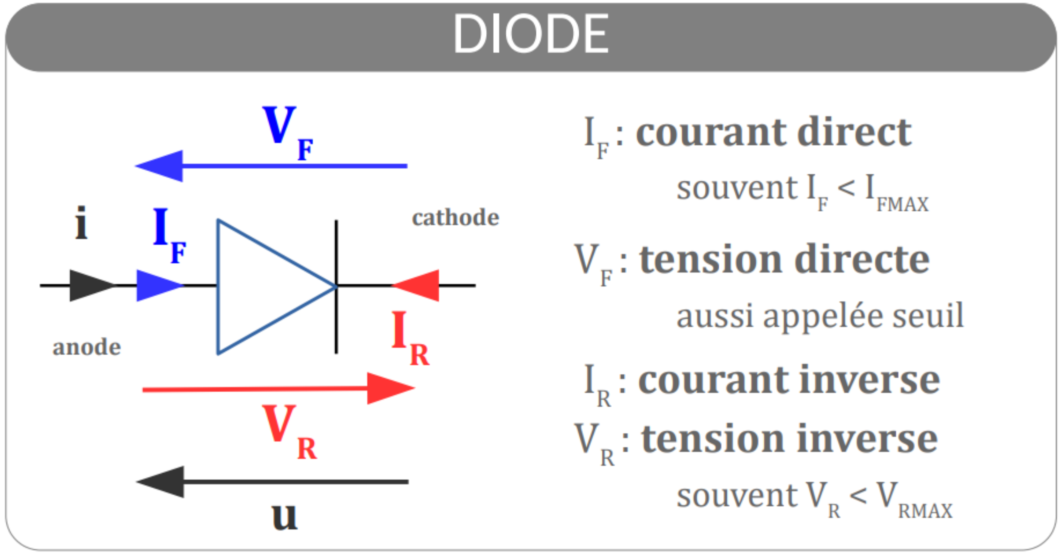
$$\eta = \frac{\text{Nb photons émis}}{\text{Nb électrons}}$$

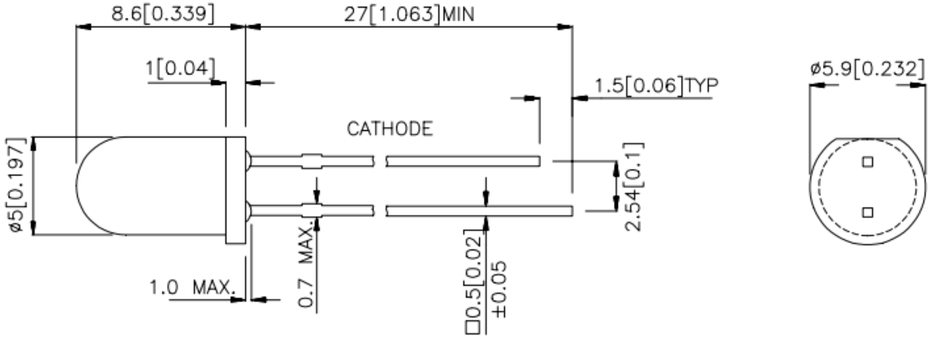
- λ : longueur d'onde d'émission

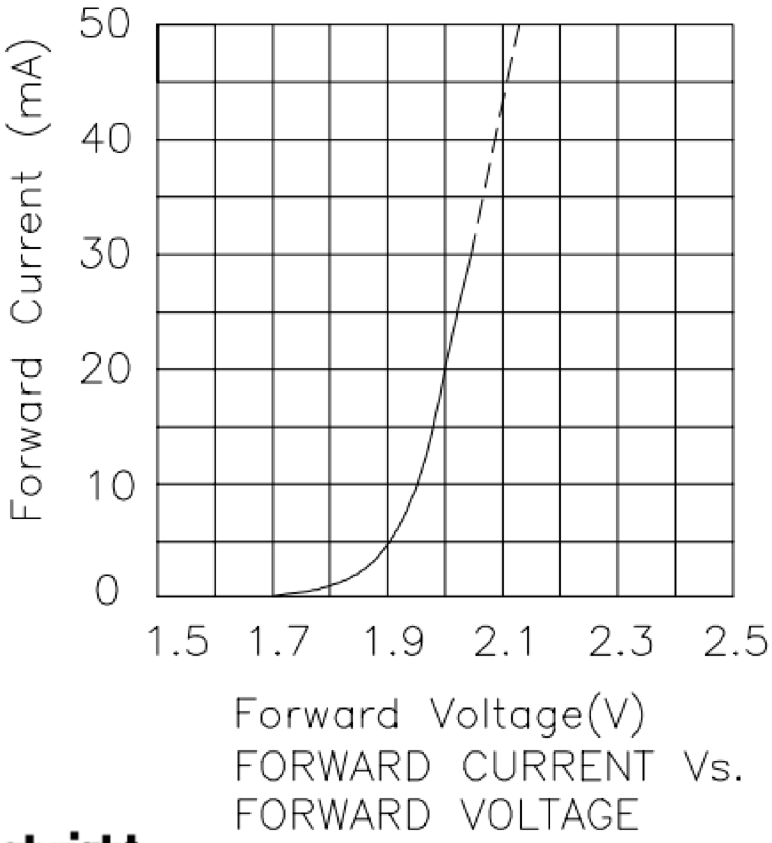


Source de photons

Caractéristiques électriques d’une LED





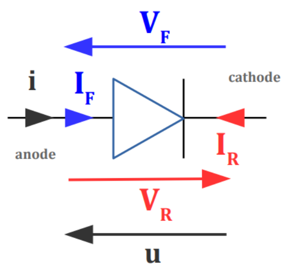


Kingbright

High Efficiency Red L-53ID

Caractéristiques électriques d'une LED

DIODE



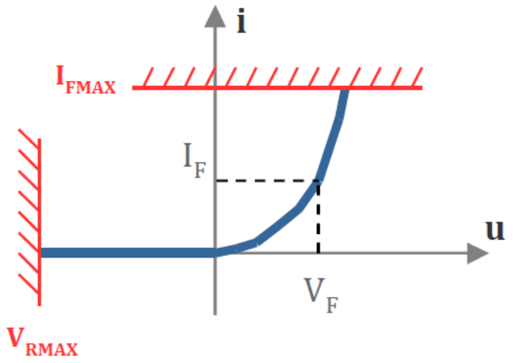
I_F : **courant direct**
souvent $I_F < I_{FMAX}$

V_F : **tension directe**
aussi appelée seuil

I_R : **courant inverse**

V_R : **tension inverse**
souvent $V_R < V_{RMAX}$

MODÈLE COMPLET



$e = -1{,}602 \times 10^{-19}$ C

$k = 1{,}38064852 \, . \, 10^{-23}$ J/K

Si u > 0, diode **passante**

$$\mathbf{i = I_0\,[\,\exp(u\,/\,n.V_0) - 1\,]}$$

loi exponentielle

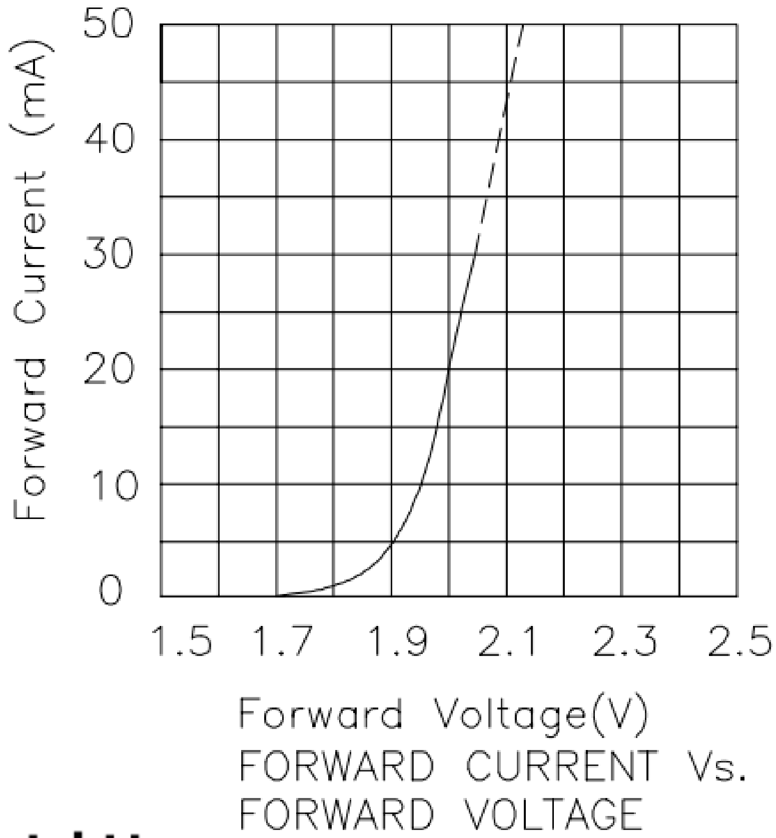
$\mathbf{V_0}$: tension thermique

$\mathbf{V_0} = k.T / e$

T : température (K)
k : Constante de Boltzmann
e : charge d'un électron

n : facteur de qualité

$\mathbf{I_0}$: constante spécifique à un type



Kingbright

High Efficiency Red **L-53ID**

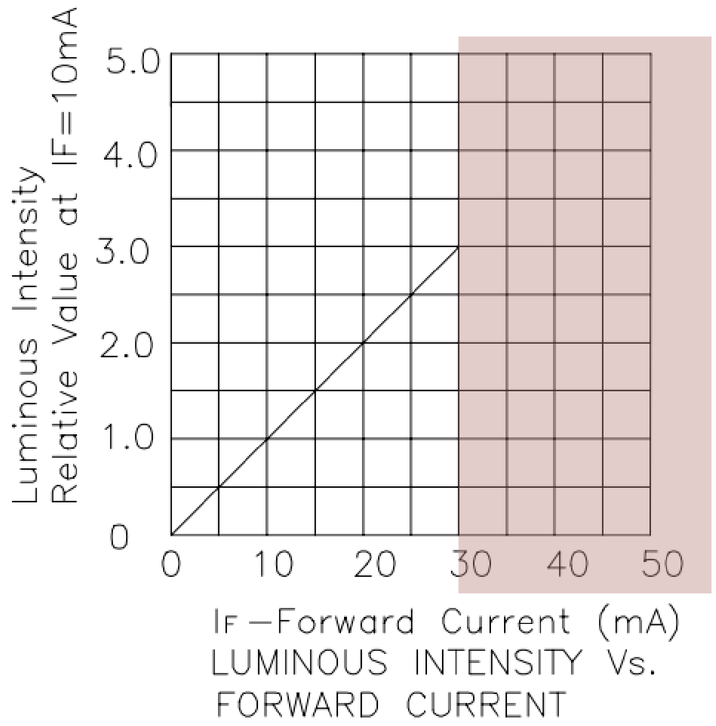
Caractéristiques électriques d'une LED

Idéalement : source de courant

Absolute Maximum Ratings at T_A=25°C

Parameter	High Efficiency Red	Units
Power dissipation	105	mW
DC Forward Current	30	mA
Peak Forward Current [1]	160	mA
Reverse Voltage	5	V
Operating/Storage Temperature	-40°C To +85°C	
Lead Solder Temperature [2]	260°C For 5 Seconds	

Notes:
1. 1/10 Duty Cycle, 0.1ms Pulse Width.
2. 2mm below package base.



Kingbright

High Efficiency Red **L-53ID**

Caractéristiques électriques d'une LED

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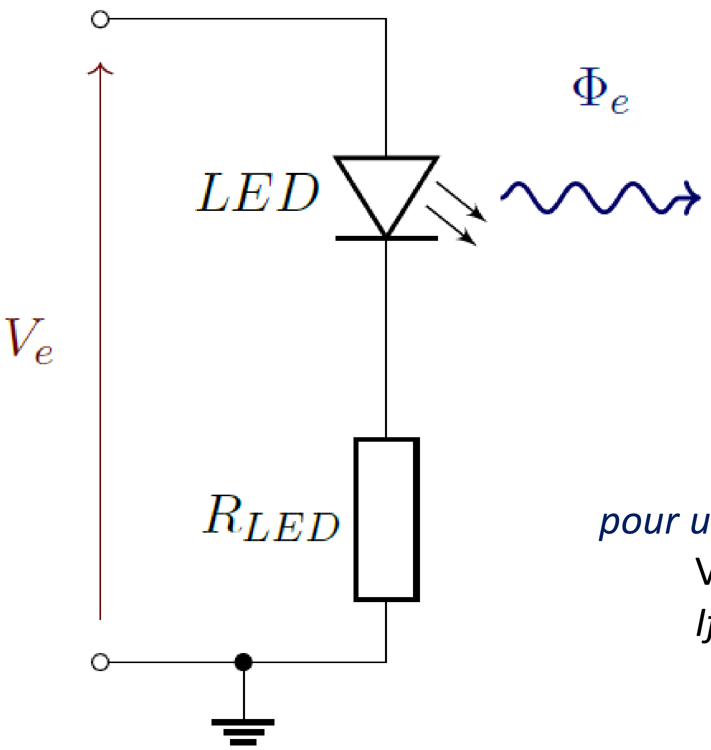

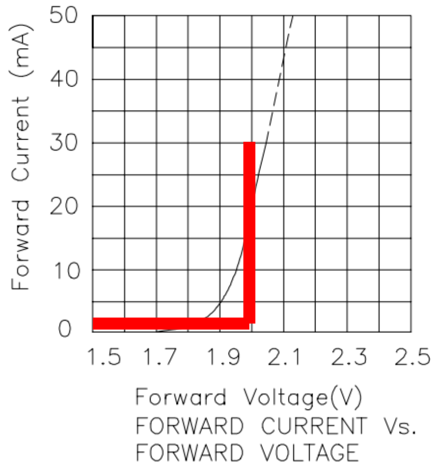

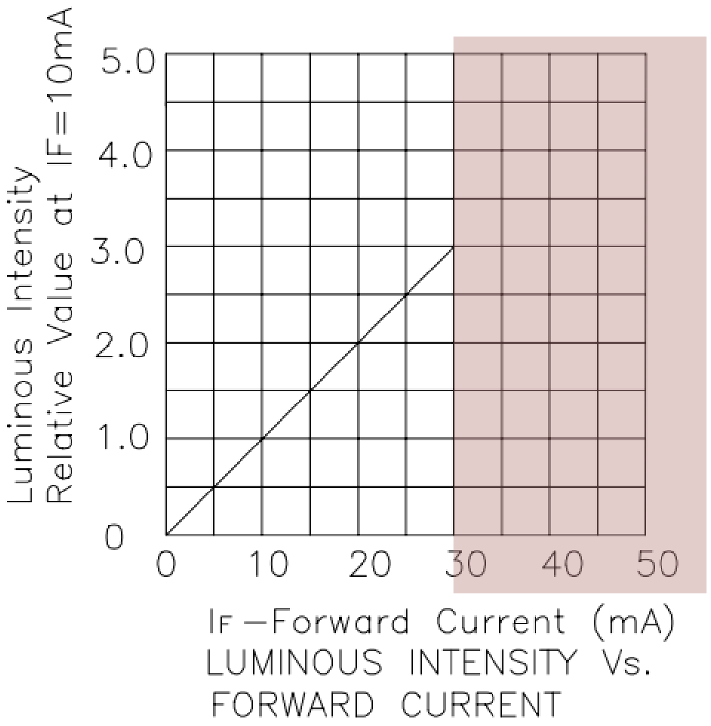

pour une LED Rouge Standard

Vf = 2V

If_{MAX} = 30 mA

High Efficiency Red **L-53ID**

Photodétection

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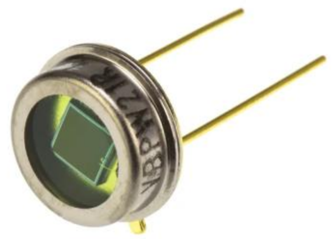
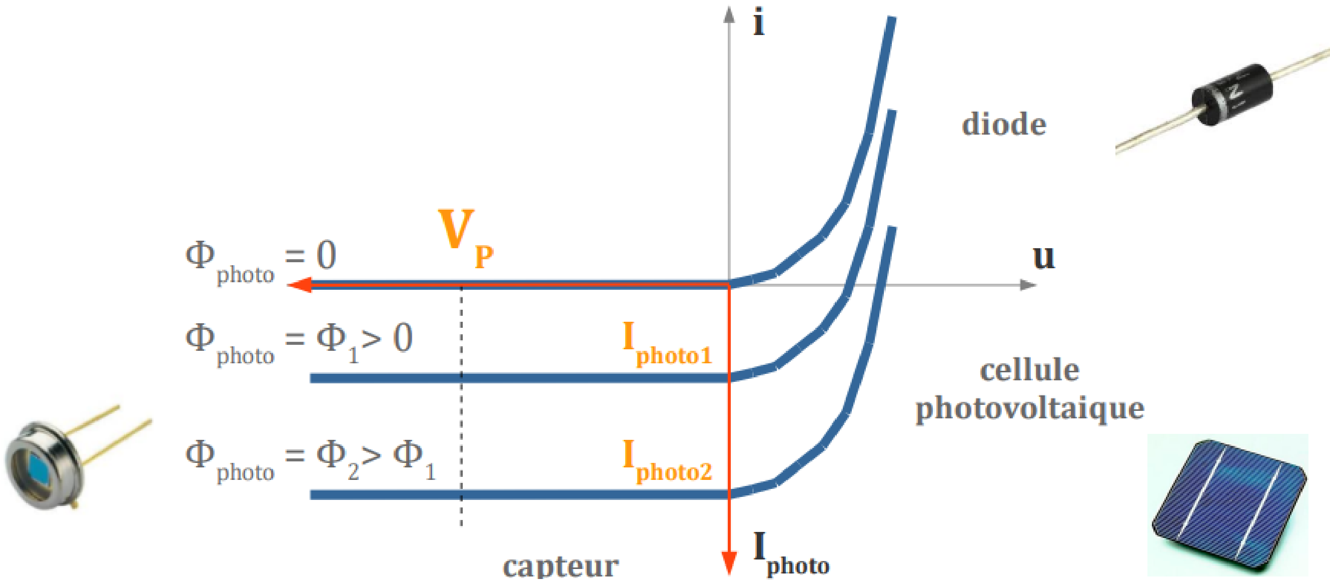
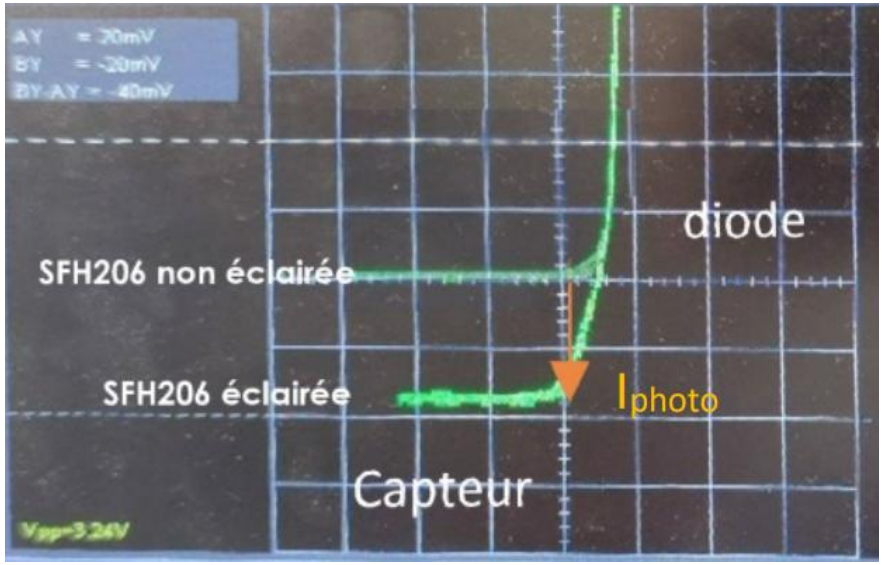
Photodiode, une diode mais…







$$\underset{A}{I_{photo}} = \underset{A/W}{S_\lambda} \cdot \eta \cdot \underset{W}{\Phi_{photo}}$$

- S_λ : Sensibilité spectrale
- η : Rendement quantique
- Φ_{photo} : Flux lumineux

https://www.youtube.com/watch?v=KgKcbW77txY

https://www.youtube.com/watch?v=rNoHLOumplk

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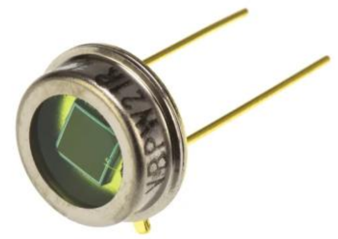
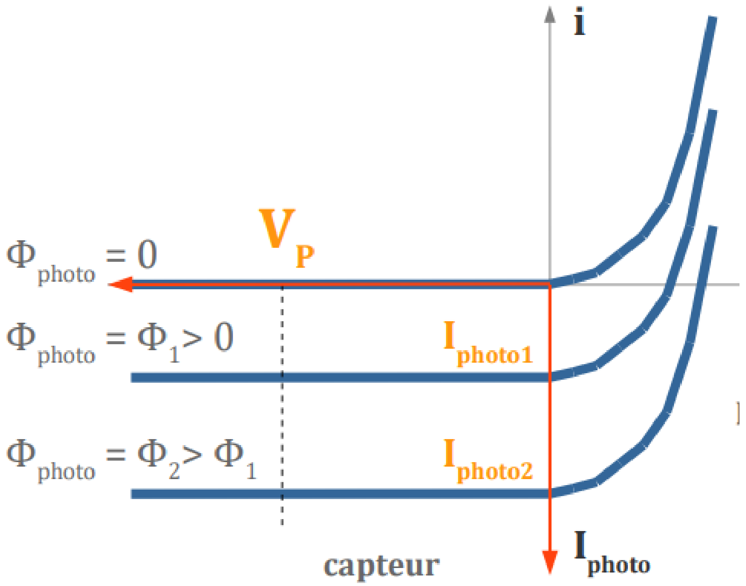




A — A/W — W

$$I_{photo} = S_\lambda \, . \, \eta \, . \, \Phi_{photo}$$

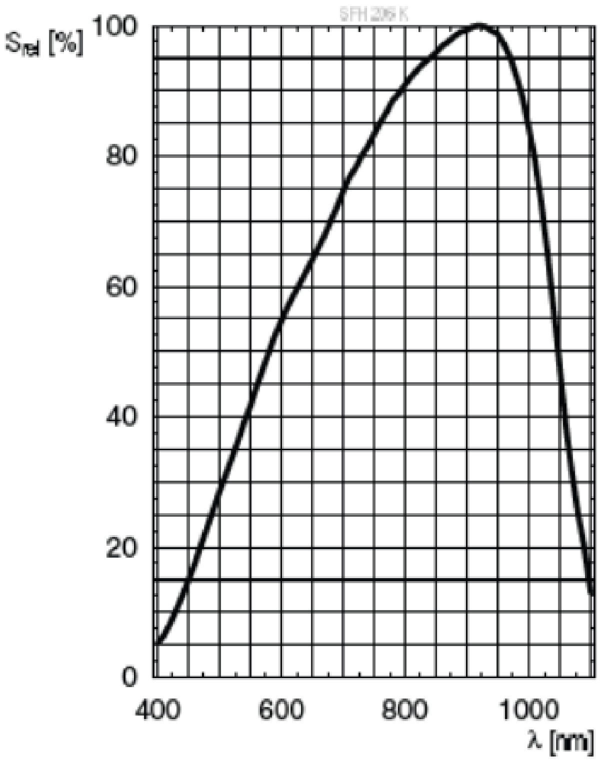
Sensibilité spectrale

Rendement quantique

Flux lumineux

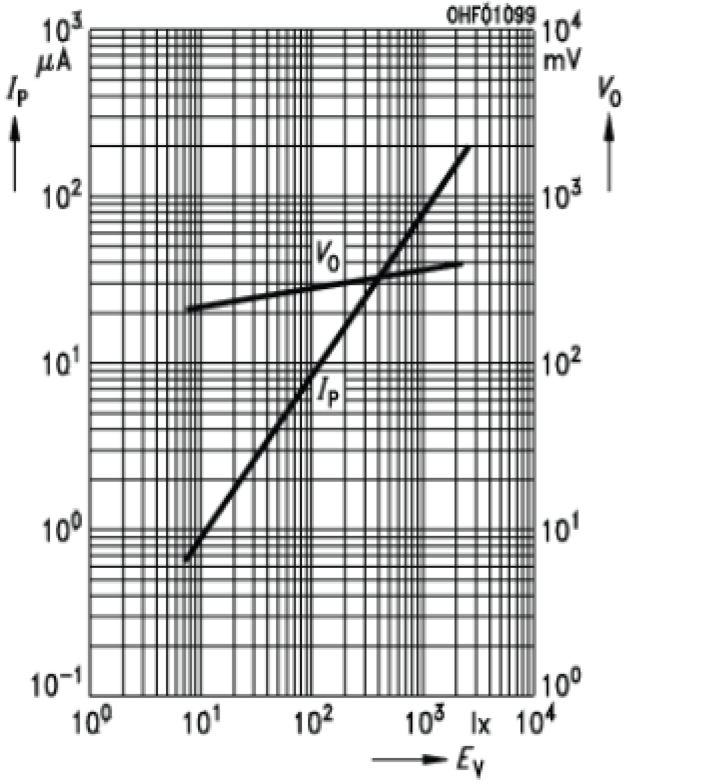
SFH 206 K

Relative Spectral Sensitivity



Photocurrent/Open-Circuit Voltage

I_P (V_R = 5 V) / V_O = f (E_v)



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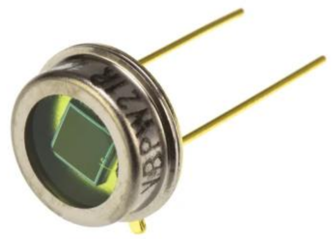
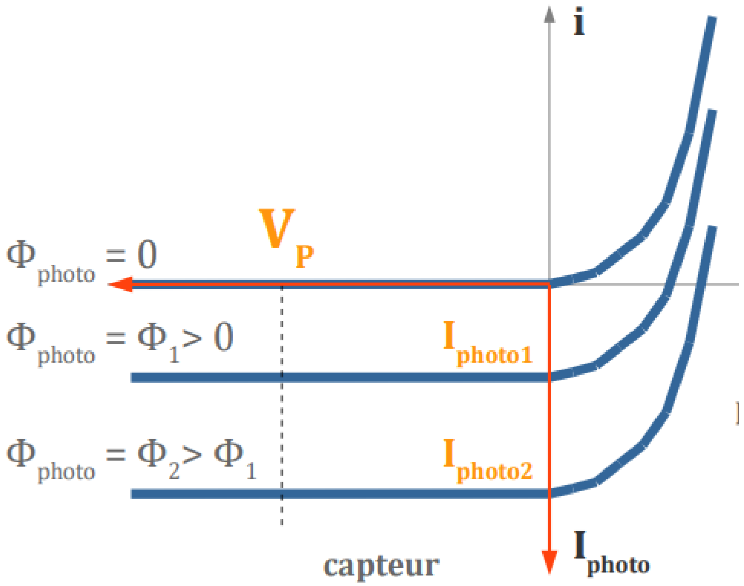




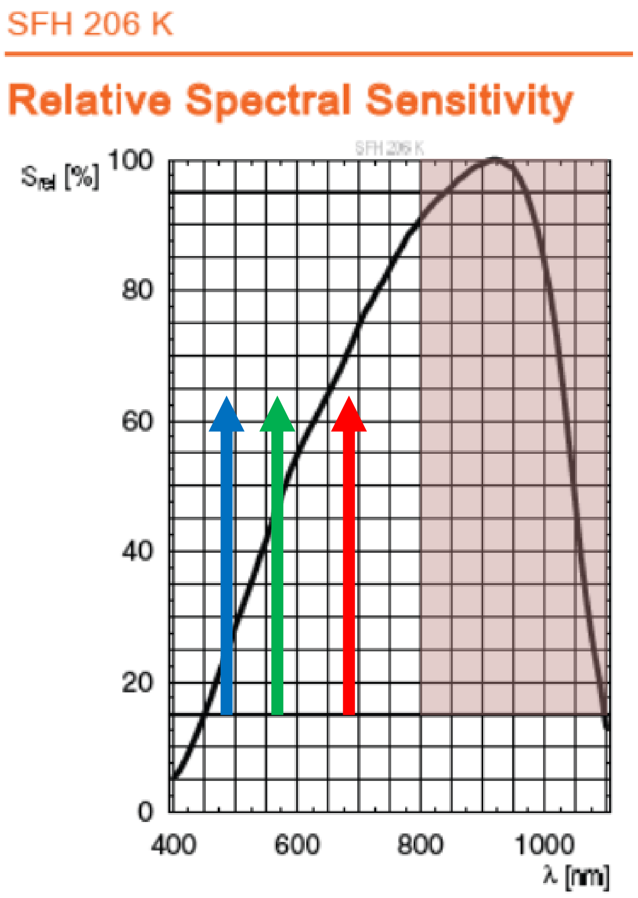
A — A/W — W

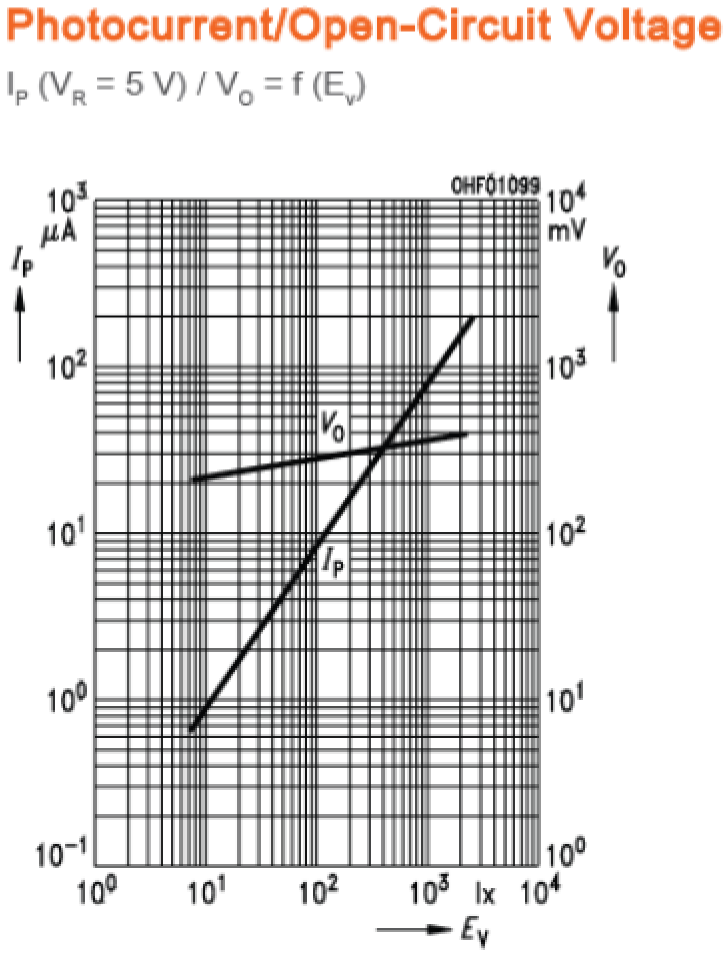
$$\boxed{I_{photo} = S_\lambda \cdot \eta \cdot \Phi_{photo}}$$

Sensibilité spectrale

Rendement quantique

Flux lumineux





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Photodétection

Montage simple

Opto-Electronique / Semestre 5
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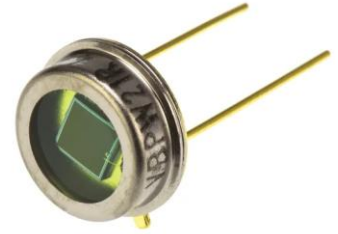
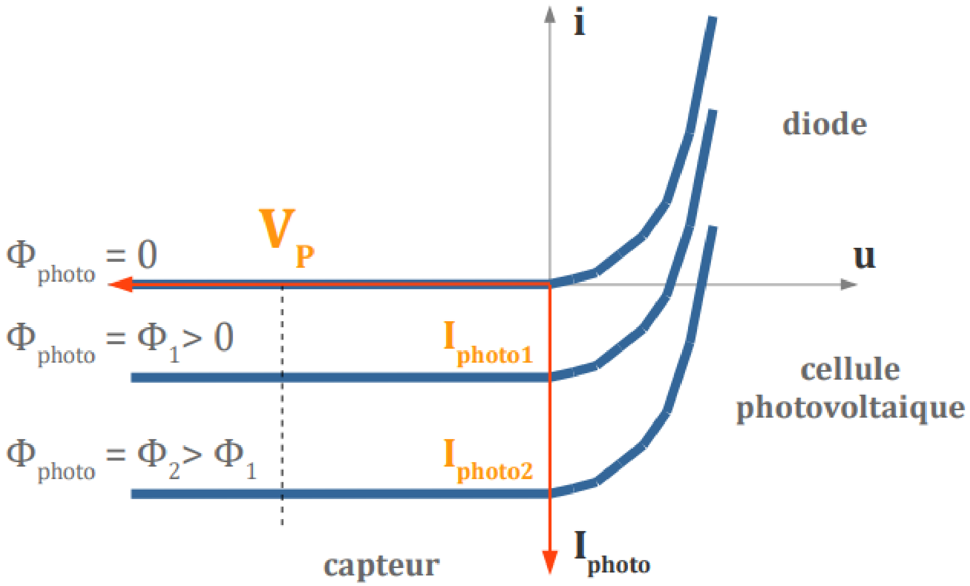
Julien VILLEMEJANE

Montage de photodétection





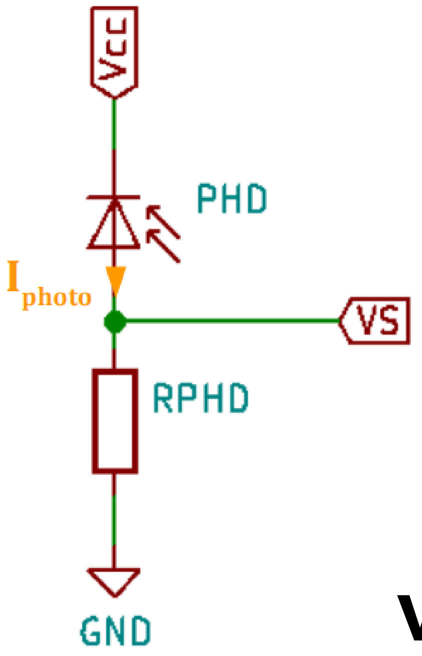
A A/W W

$$\boxed{I_{photo} = S_\lambda \cdot \eta \cdot \Phi_{photo}}$$

Sensibilité spectrale

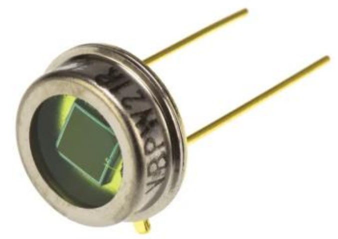
Rendement quantique

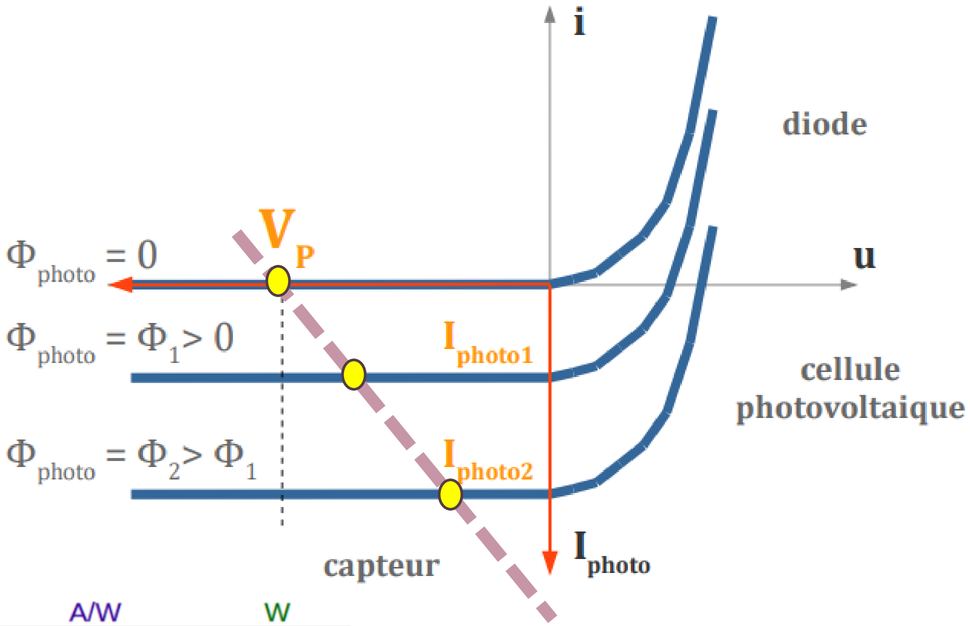
Flux lumineux



$$V_S = R_{PHD} \cdot I_{photo}$$

Montage de photodétection





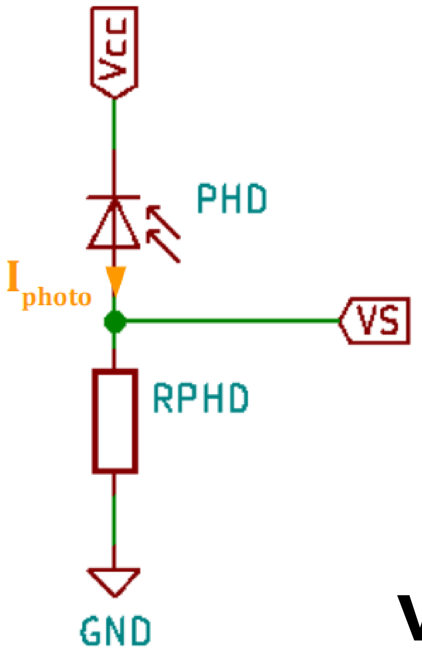
A A/W W

$$I_{photo} = S_\lambda \cdot \eta \cdot \Phi_{photo}$$

Sensibilité spectrale

Rendement quantique

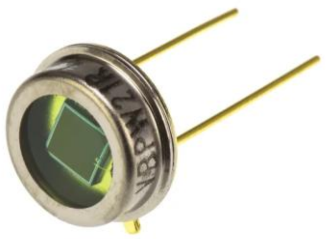
Flux lumineux

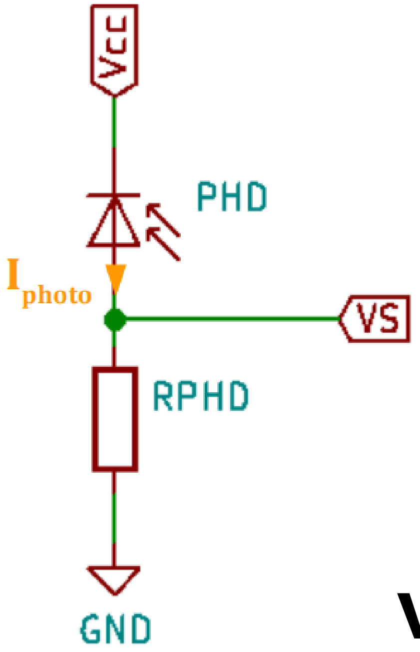


$$V_S = R_{PHD} \cdot I_{photo}$$

Tension de polarisation non constante

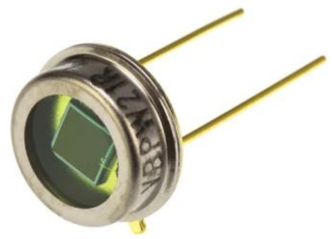
Etude expérimentale



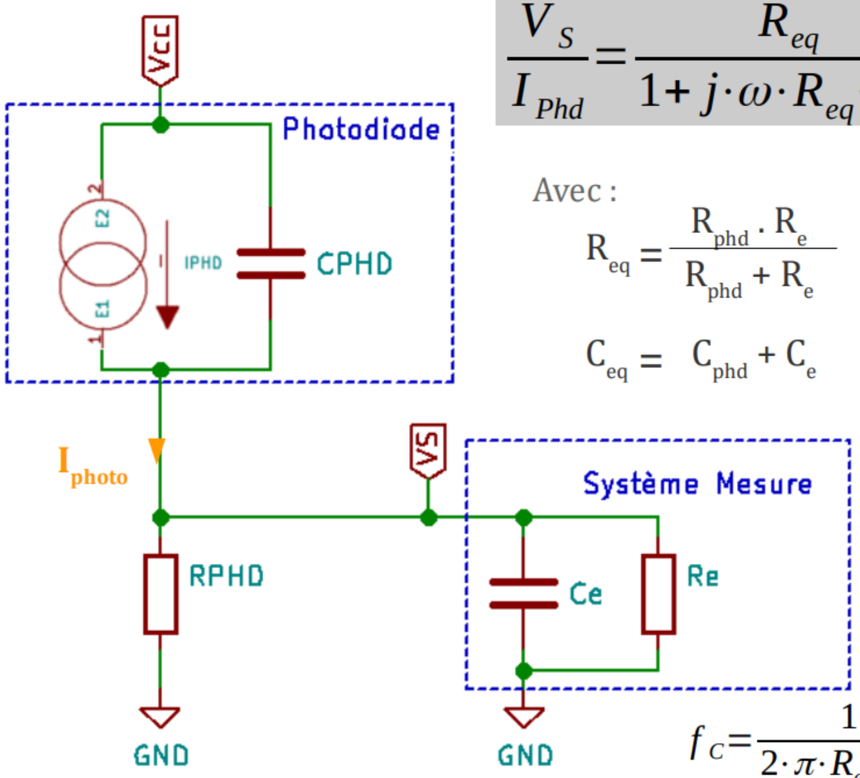


$$V_S = R_{PHD} \cdot I_{photo}$$

Modélisation



Bande passante réduite (à cause du système de mesure)



$$\frac{V_S}{I_{Phd}} = \frac{R_{eq}}{1 + j \cdot \omega \cdot R_{eq} \cdot C_{eq}}$$

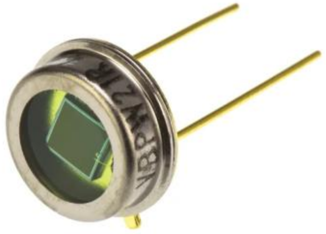
Avec :

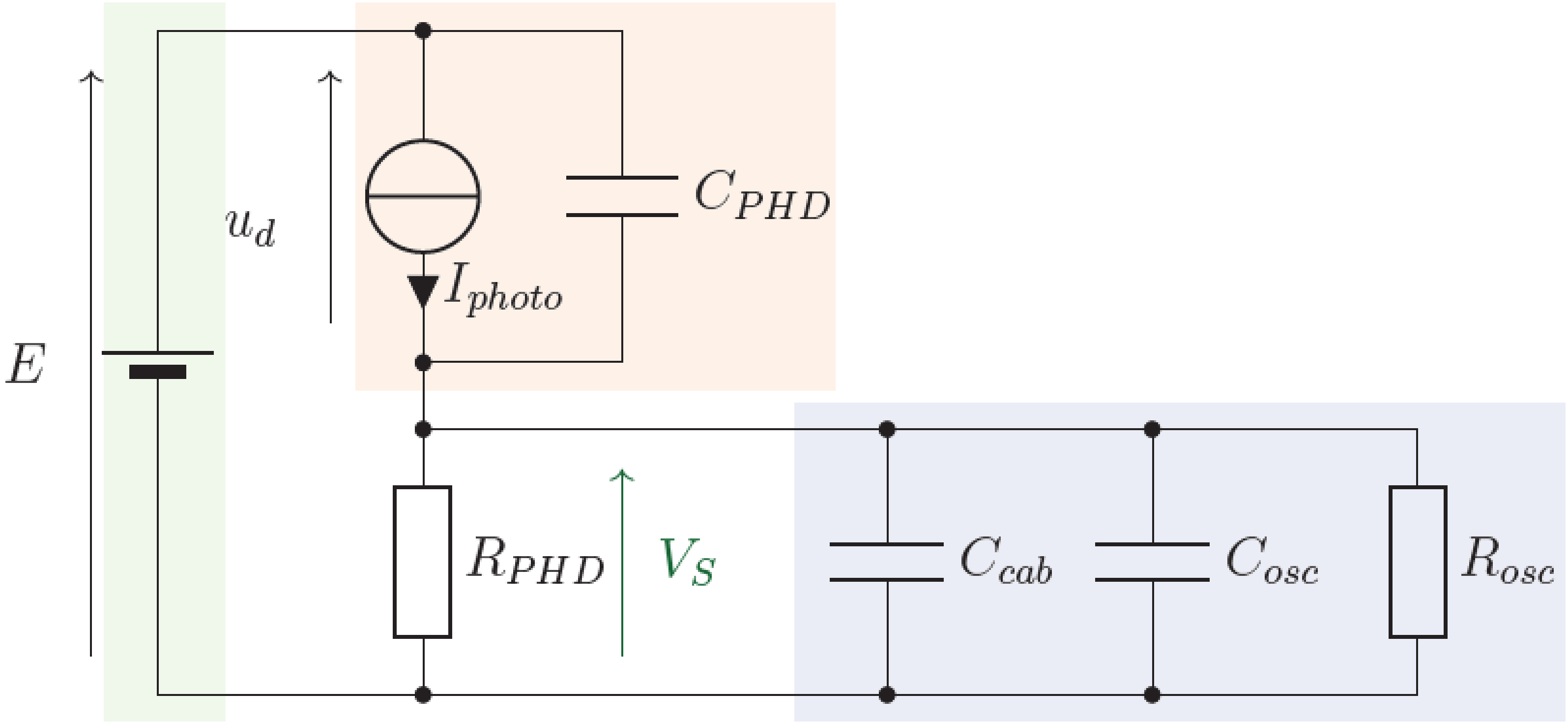
$$R_{eq} = \frac{R_{phd} \cdot R_e}{R_{phd} + R_e}$$

$$C_{eq} = C_{phd} + C_e$$

$$f_C = \frac{1}{2 \cdot \pi \cdot R_{eq} \cdot C_{eq}}$$

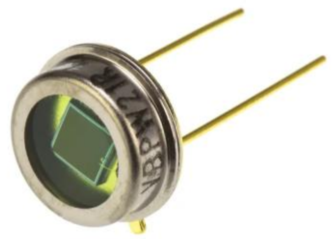
Modélisation

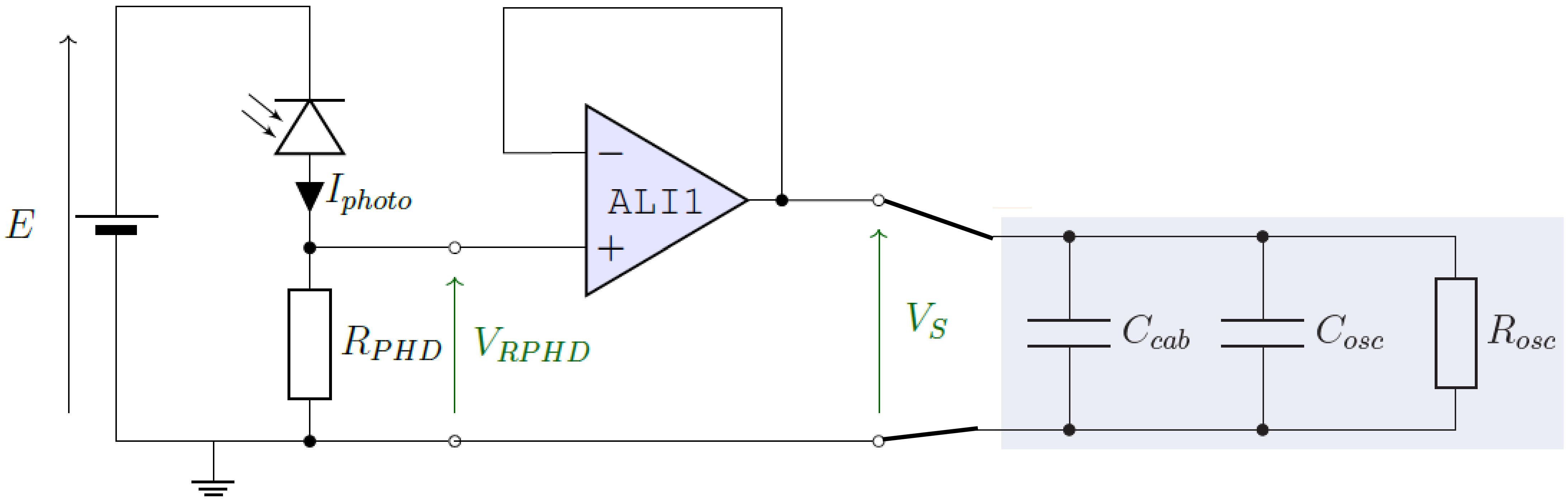




Bande passante réduite (à cause du système de mesure)

Amélioration / Montage Suiveur





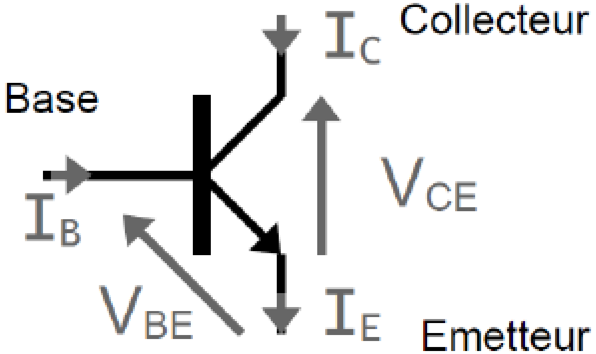
Transistor

Opto-Electronique / Semestre 5
Institut d'Optique

Julien VILLEMEJANE

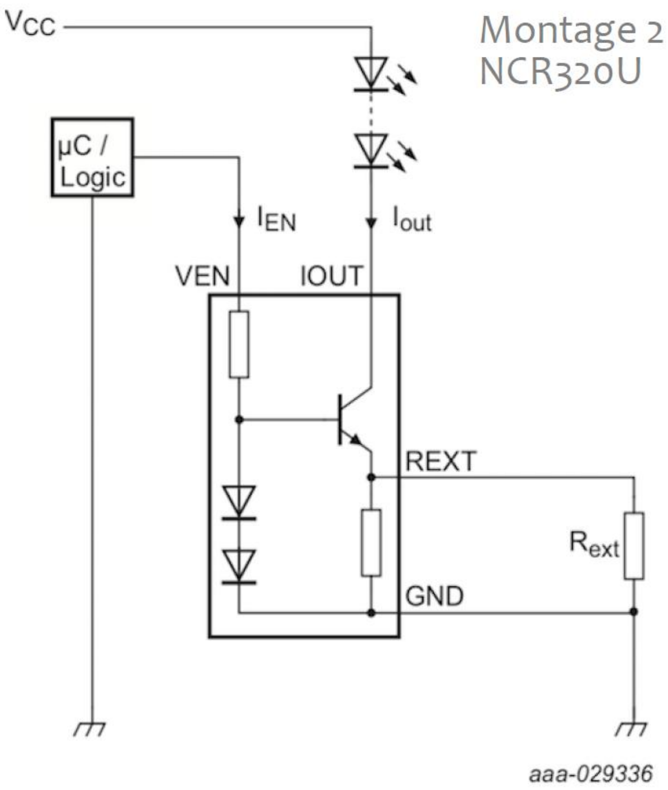
Transistor (bipolaire)

Adaptation de puissance



$$I_C = \beta \cdot I_B \qquad et \qquad I_E = I_C + I_B$$

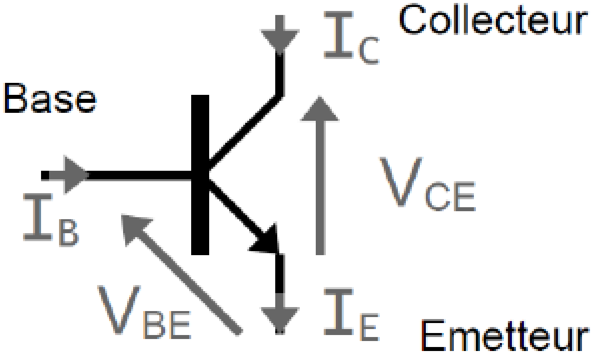
$$I_C = \beta \cdot I_{BS} \cdot \exp(V_{BE}/U_T)$$



Montage 2
NCR320U

Transistor (bipolaire)

Adaptation de puissance



$$I_C = \beta \cdot I_B \qquad et \qquad I_E = I_C + I_B$$

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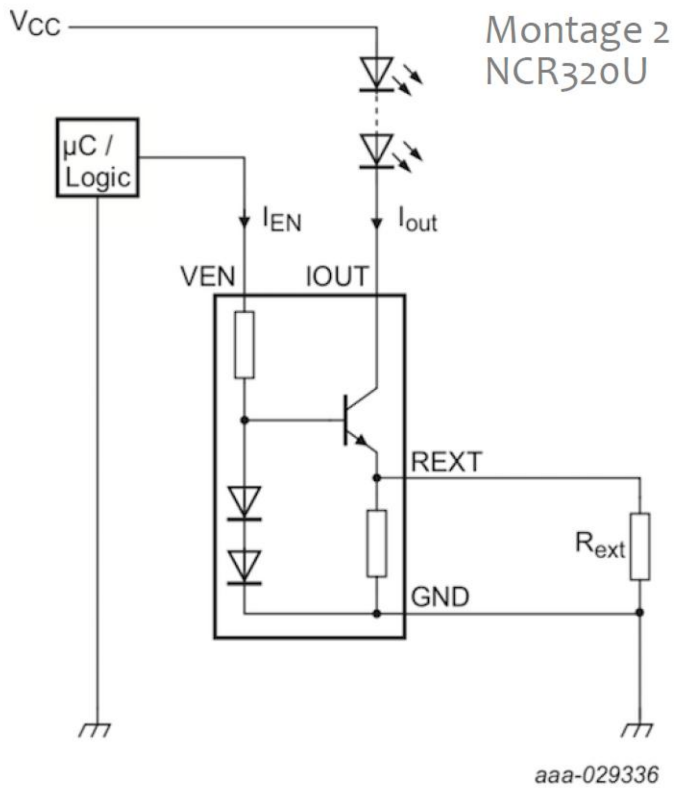

Montage 2
NCR320U

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ALI / Amplificateur Linéaire Intégré

Opto-Electronique / Semestre 5
Institut d'Optique

Julien VILLEMEJANE

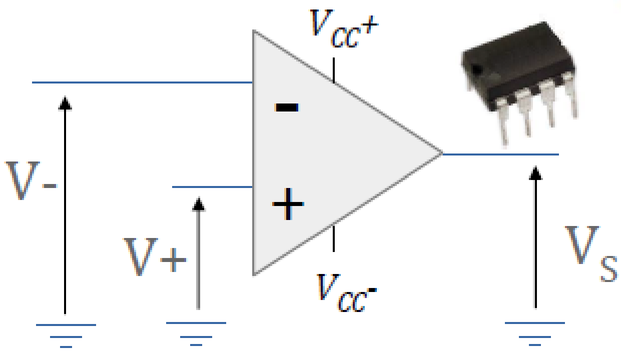
Amplificateur linéaire intégré / ALI

FONCTION DE TRANSFERT

$$V_S = A\,.\,(V+ \;-\; V-)$$

avec $10^5 < A < 10^7$

Saturation à $Vs = V_{cc}+$



Amplificateur linéaire intégré / ALI

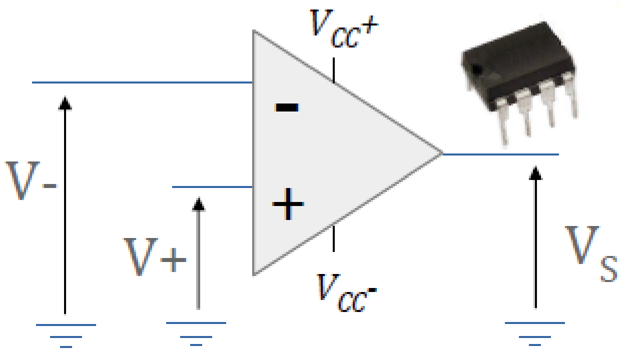
Fonctionnement boucle ouverte : comparateur

FONCTION DE TRANSFERT

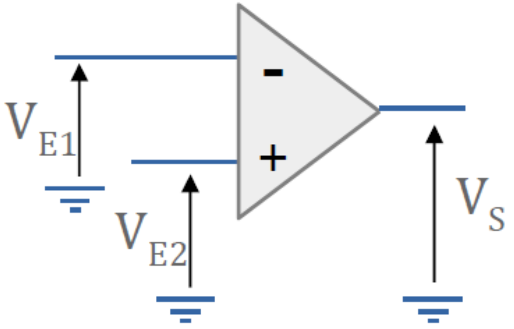
$$V_S = A\,.\,(V+\ -\ V-)$$

avec $10^5 < A < 10^7$

Saturation à $Vs = V_{cc}+$



COMPARATEUR SIMPLE



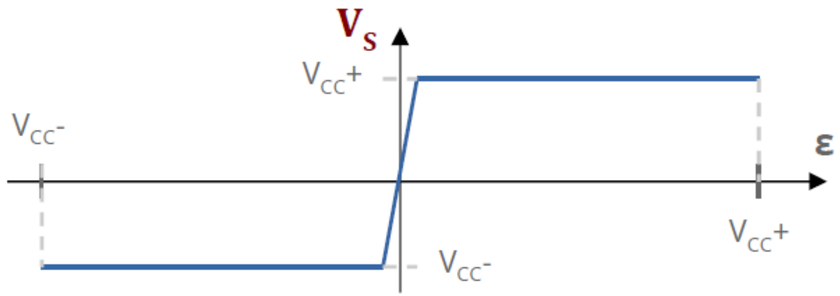
$$V_S = V_{CC}+$$

Si $V_{E2} > V_{E1}$

$$V_S = V_{CC}-$$

Si $V_{E1} > V_{E2}$

Caractéristique Vs = f (ε) avec $\varepsilon = V+ - V-$



Amplificateur linéaire intégré / ALI

Fonctionnement boucle ouverte : comparateur / Collecteur ouvert

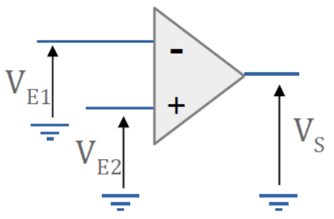
FONCTION DE TRANSFERT

$$V_S = A\,.\,(V+ \; - \; V-)$$

avec $10^5 < A < 10^7$

Saturation à $Vs = V_{CC}+$

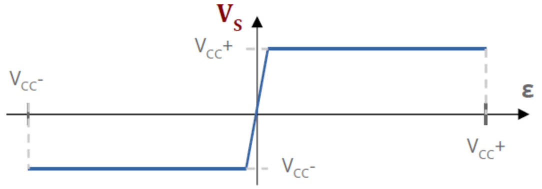
COMPARATEUR SIMPLE



$V_S = V_{CC}+$ Si $V_{E2} > V_{E1}$

$V_S = V_{CC}-$ Si $V_{E1} > V_{E2}$

Caractéristique Vs = f (ε) avec ε = V+ - V-



COLLECTEUR OUVERT / ÉMETTEUR OUVERT

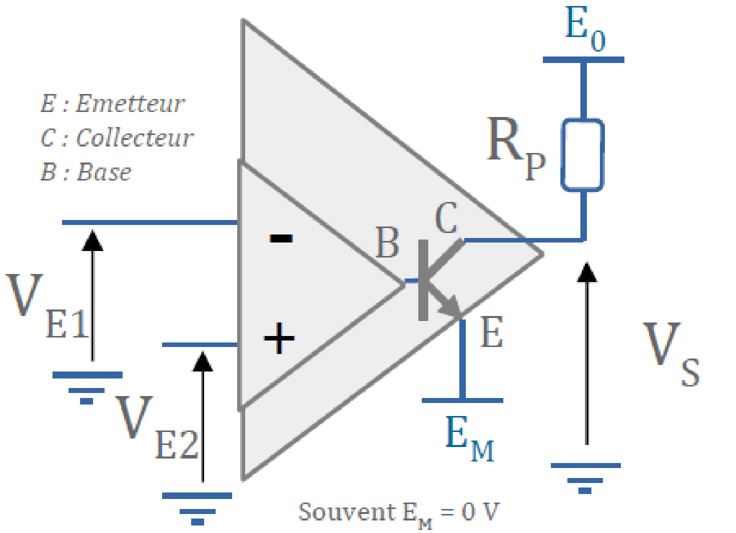
Comparateur associé à un transitor T :

I_B : courant entrant dans la base

I_C : courant entrant dans le collecteur

→ si $I_B > 0$ alors $I_C > 0$, T = interrupteur fermé

→ sinon $I_C = 0$, T = interrupteur ouvert



Si $V_{E2} > V_{E1}$ → $I_B > 0$

$$V_S = E_M$$

Si $V_{E1} > V_{E2}$ → $I_B = 0$

$$V_S = E_0$$

Amplificateur linéaire intégré / ALI

Fonctionnement boucle fermée : mode linéaire

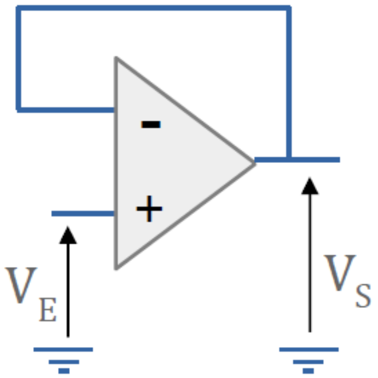
FONCTION DE TRANSFERT

$$V_S = A\,.\,(V+ \; - \; V-)$$

avec $10^5 < A < 10^7$

Saturation à $V_s = V_{cc}+$

SUIVEUR



$$V_S = V_E$$

Adaptation d'impédance

Si contre-réaction négative (via un dipôle)

▶ REGIME LINEAIRE

▶ V+ = V-

Hypothèse à vérifier…

Amplificateur linéaire intégré / ALI

Fonctionnement boucle fermée : mode linéaire

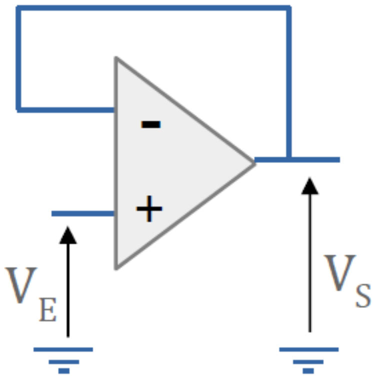
FONCTION DE TRANSFERT

$$V_S = A\,.\,(V+ \; - \; V-)$$

avec $10^5 < A < 10^7$

Saturation à $Vs = V_{cc}+$

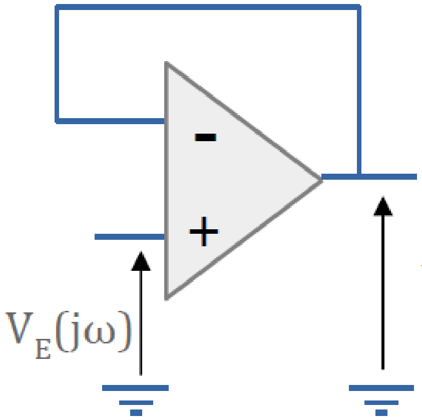
SUIVEUR



$$V_S = V_E$$

Adaptation d'impédance

FONCTION DE TRANSFERT EN SUIVEUR



A partir de l'équation ci-contre, on obtient pour ce circuit (suiveur) :

$$V_S(j\omega) = A(j\omega)\,.\,[V_E(j\omega) \; - \; V_S(j\omega)]$$

On obtient la fonction de transfert suivante :

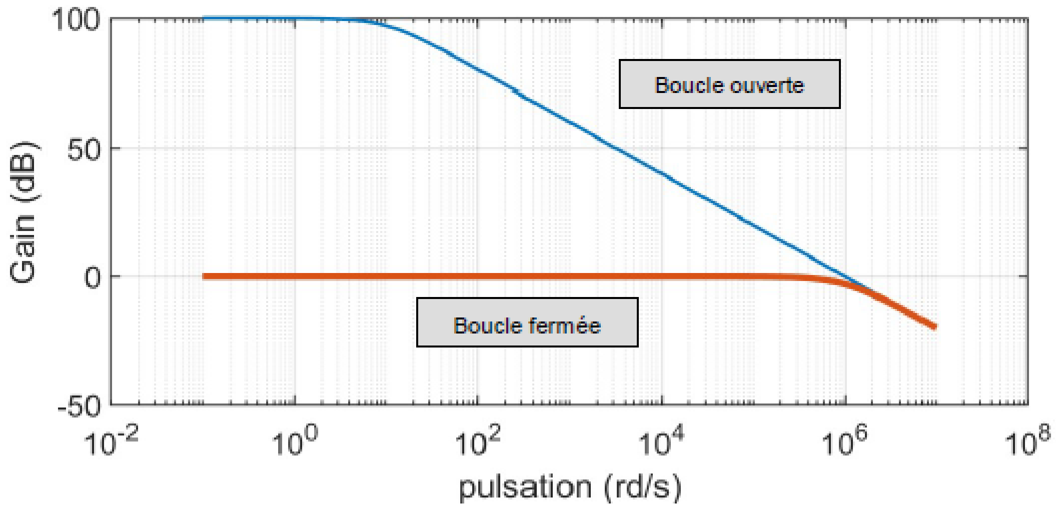
$$T(j\omega) = \frac{V_S(j\omega)}{V_E(j\omega)} = \frac{A(j\omega)}{1 + A(j\omega)}$$

Amplificateur linéaire intégré / ALI

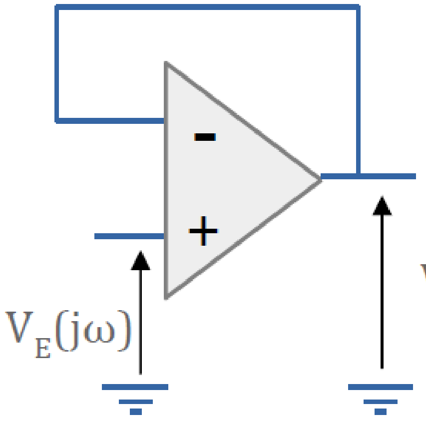
Fonctionnement boucle fermée : mode linéaire

RÉPONSE EN FRÉQUENCE

Exemple d'un ALI ayant un produit gain – bande-passante GBW = 1 MHz et une amplification différentielle de 10^5 (identique ci-contre) et le rebouclage en mode suiveur.



FONCTION DE TRANSFERT EN SUIVEUR



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Amplificateur linéaire intégré / ALI

Fonctionnement boucle fermée : mode linéaire

RÉPONSE EN FRÉQUENCE

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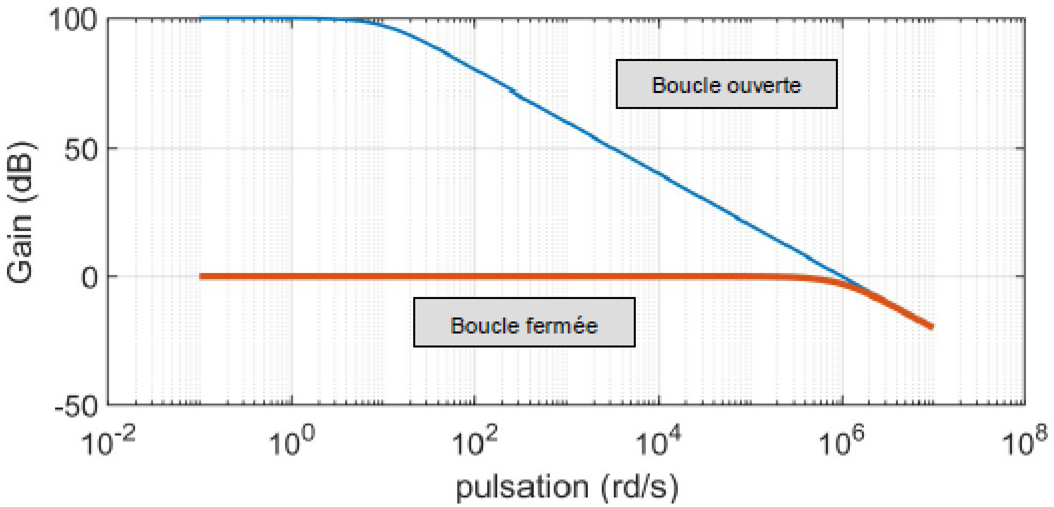

Propriété des montages à ALI

- A.BP = cte

Où A est l'amplification du montage
BP la bande passante du montage

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Photodétection

Montage transimpédance

Opto-Electronique / Semestre 5
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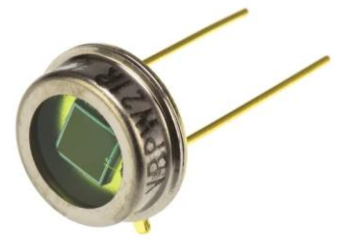
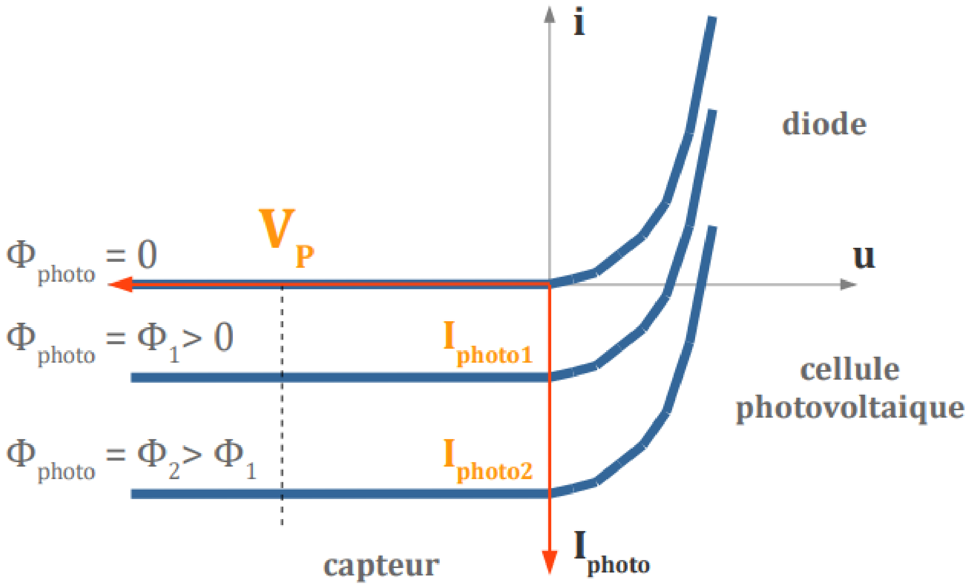
Montage transimpédance





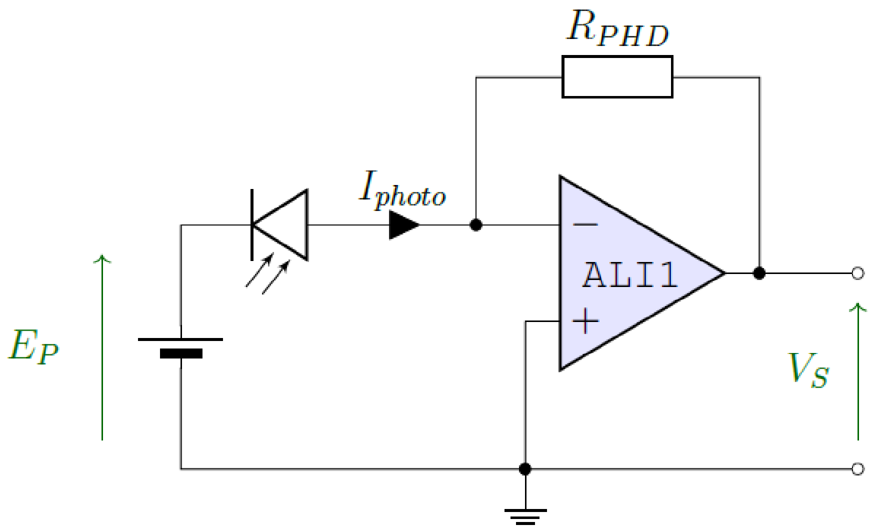
A | A/W | W

$$\boxed{I_{photo} = S_\lambda \, . \, \eta \, . \, \Phi_{photo}}$$

Sensibilité spectrale

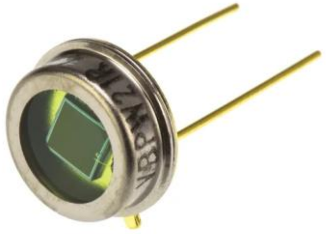
Rendement quantique

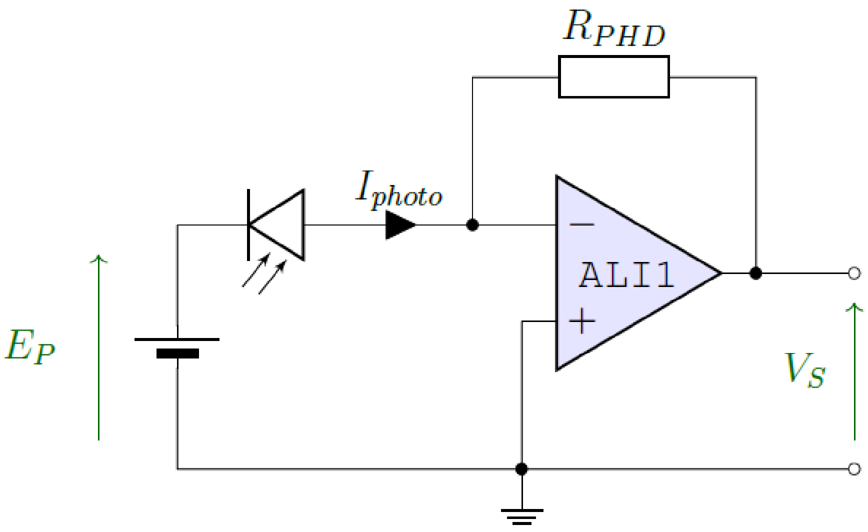
Flux lumineux



$$\mathbf{V_S = -\,R_{PhD} \cdot I_{photo}}$$

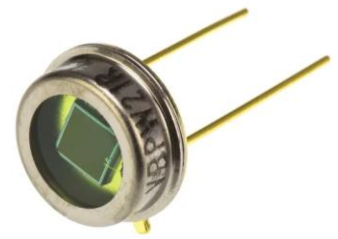
Etude expérimentale

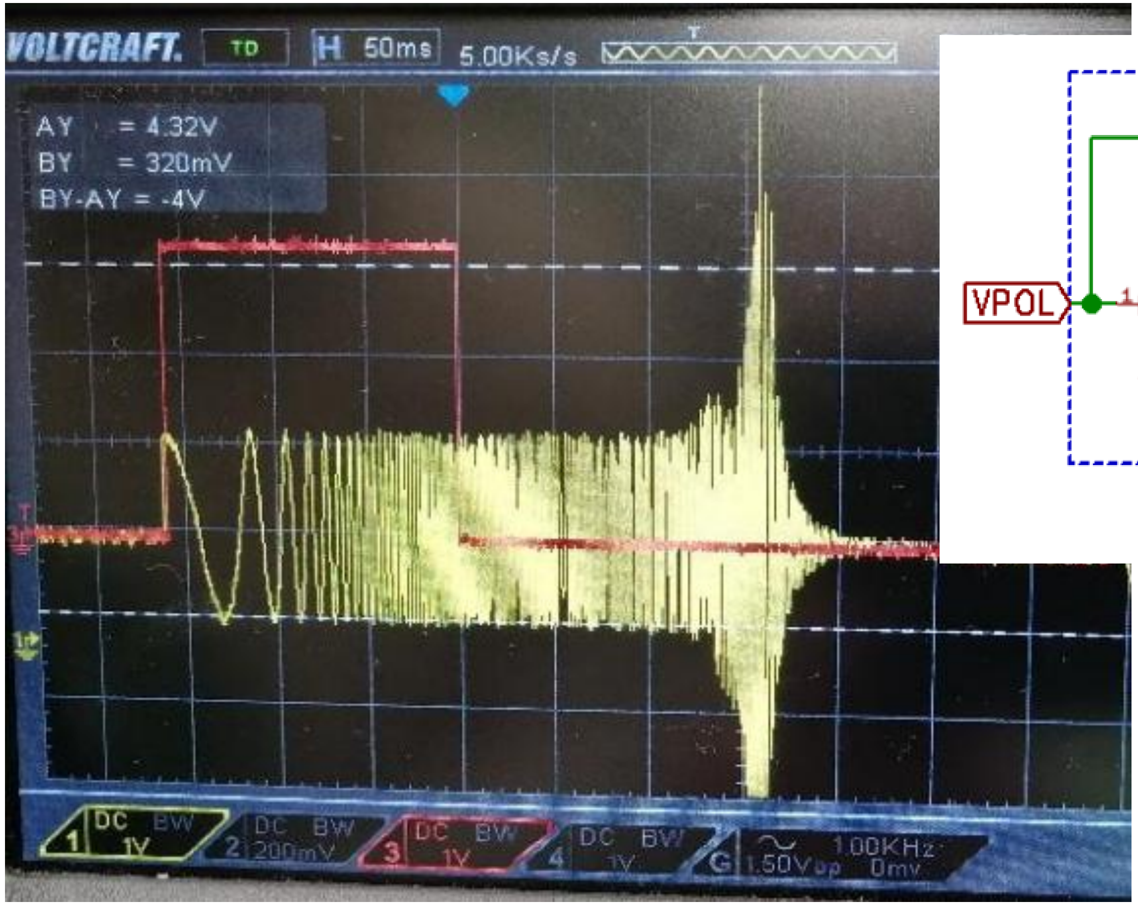


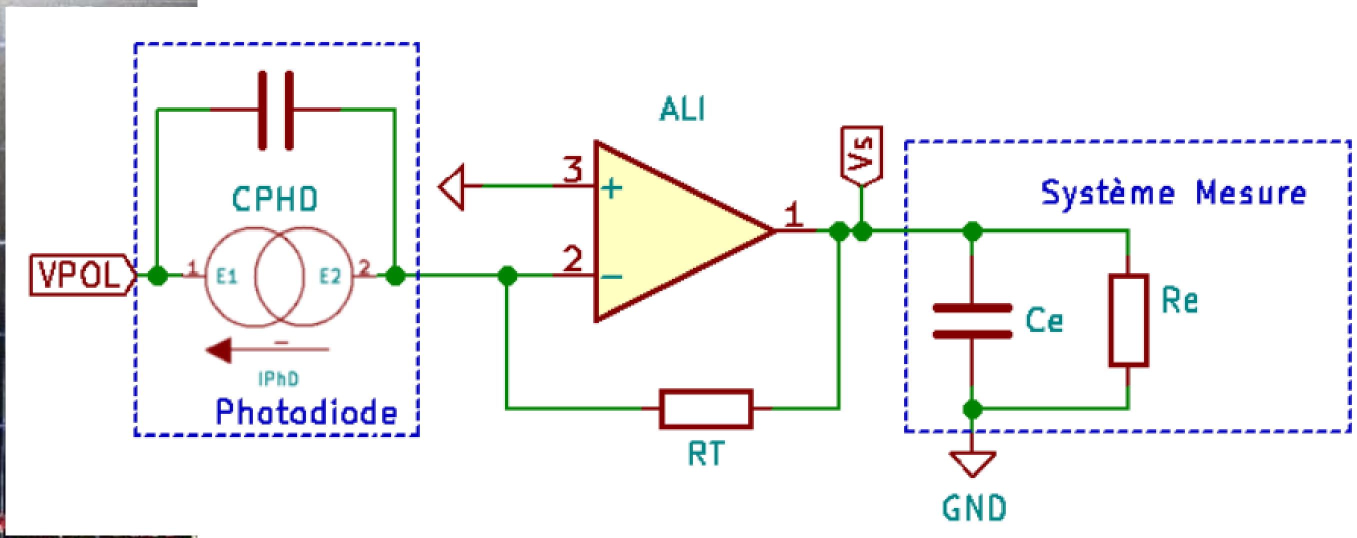


$$\mathbf{V_S = -R_{PhD} \cdot I_{photo}}$$

Modélisation







ALI / Passe-bas

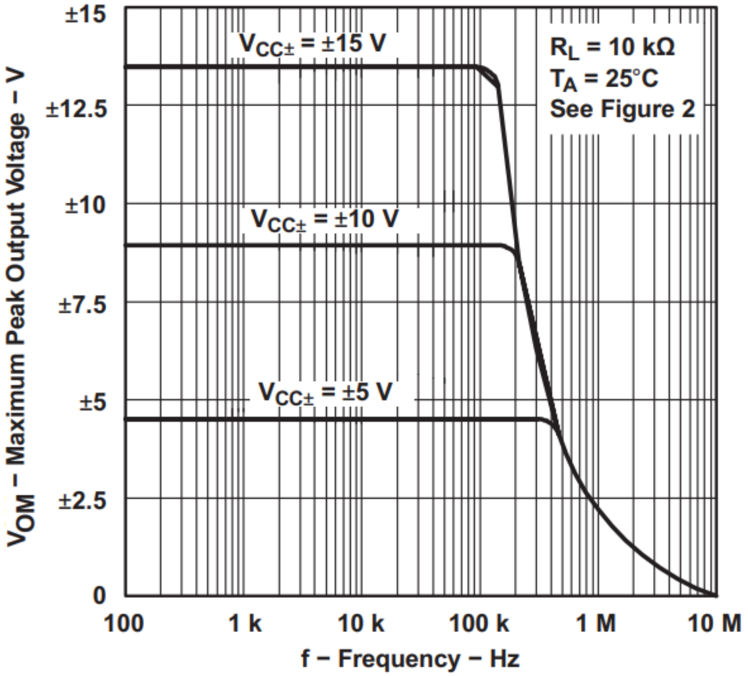


Figure 6-41. Maximum Peak Output Voltage vs Frequency

Produit Gain-Bande-Passante constant

INPUT CAPACITANCE						
Z_{ID}	Differential			100 || 2		MΩ || pF
Z_{ICM}	Common-mode			6 || 1		TΩ || pF
OPEN-LOOP GAIN						
A_{OL}	Open-loop voltage gain	V_S = 40 V, $V_{CM} = V_S / 2$, $(V_{CC-}) + 0.3\ V < V_O < (V_{CC+}) - 0.3\ V$	118	125		dB
A_{OL}	Open-loop voltage gain	V_S = 40 V, $V_{CM} = V_S / 2$, R_L = 2 kΩ, $(V_{CC-}) + 1.2\ V < V_O < (V_{CC+}) - 1.2\ V$	115	120		dB
FREQUENCY RESPONSE						
GBW	Gain-bandwidth product			5.25		MHz
SR	Slew rate	V_S = 40 V, G = +1, C_L = 20 pF		20		V/µs

ALI asservi / Modélisation

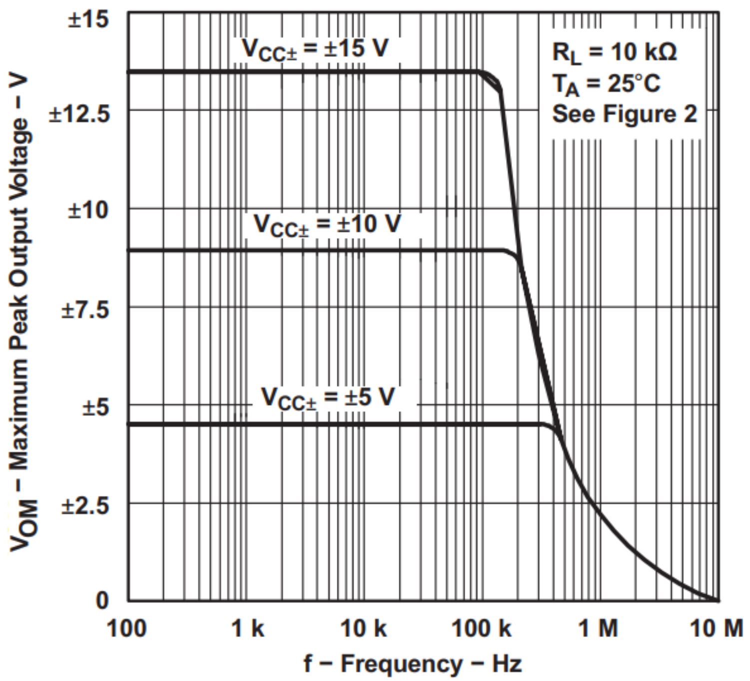
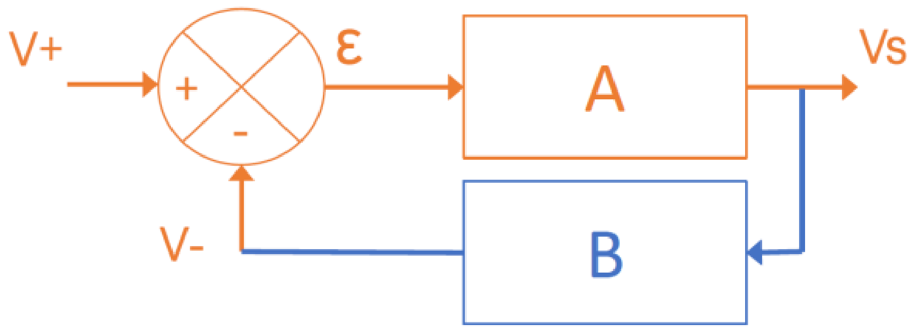


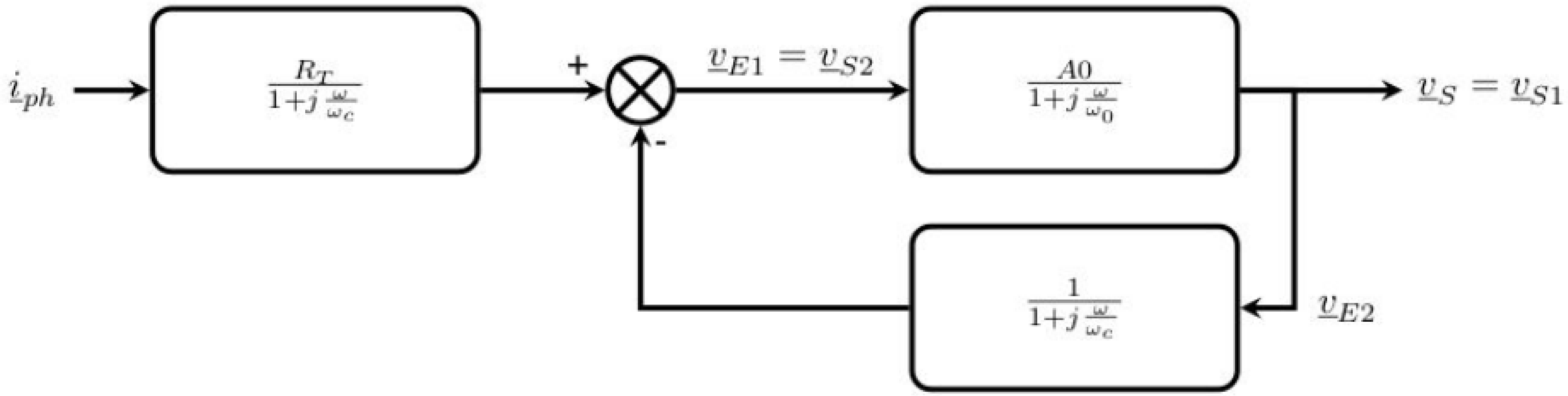
Figure 6-41. Maximum Peak Output Voltage vs Frequency

$$A(j\omega) = \frac{A_{MAX}}{1 + j\dfrac{\omega}{\omega_c}}$$



$$V_S = \frac{A(j\omega)}{1 + A(j\omega)\,.\,B(j\omega)}\,V_E$$

Transimpédance / Modélisation



$$\frac{V_S}{I_{Phd}} = \frac{R_T \cdot A_0}{\left(1+\frac{j\cdot\omega}{\omega_0}\right)\cdot\left(1+\frac{j\cdot\omega}{\omega_c}\right)+A_0}$$

$$V_S = \frac{A(j\omega)}{1 + A(j\omega)\,.\,B(j\omega)}\,V_E$$