

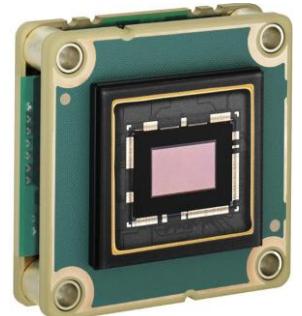
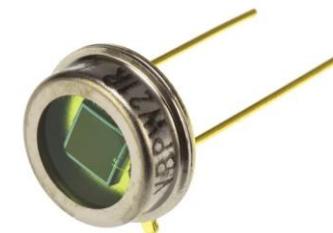
Bases de la photodétection

Module OPTO-ELECTRONIQUE

Julien VILLEMEJANE

« Si tu veux être ingénieur·e en photonique, capable de concevoir, intégrer, tester et améliorer des systèmes photoniques, tu dois savoir parler la langue de l'électronique aussi bien que celle de la lumière. »

ChatGPT



Basler Sensor / Mouser

La lumière et la photonique

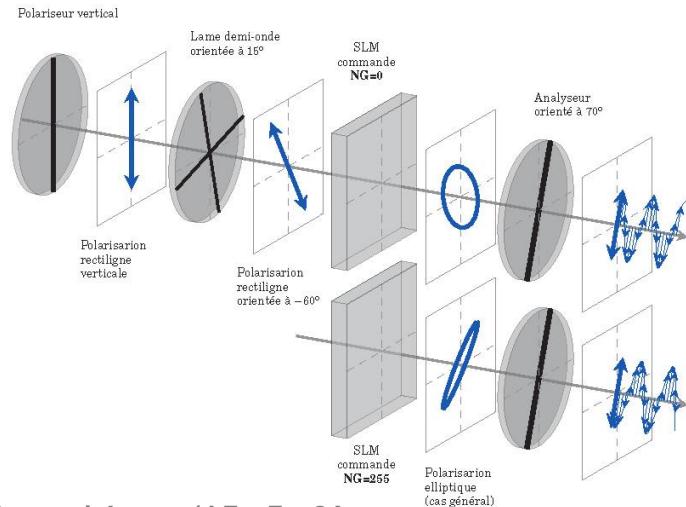
Lumière : vecteur d'informations

Schémas et image empruntés au cours d'optique instrumentale (SC19) de Sébastien de ROSSI

Lumière

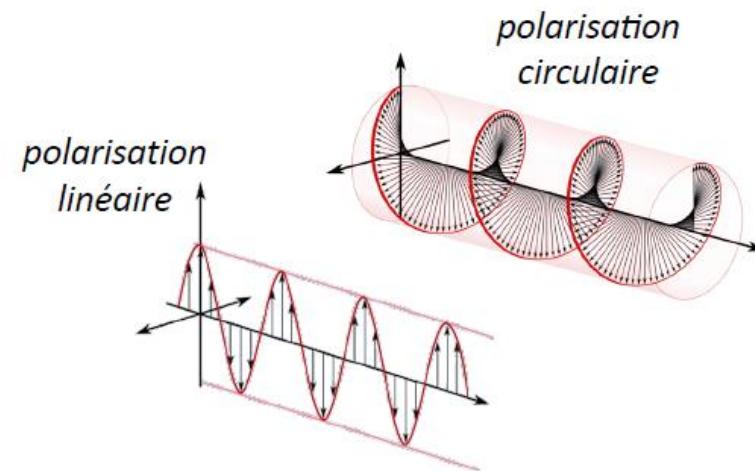
La lumière est une **onde électromagnétique transversale** définie par sa **longueur d'onde** et sa **polarisation**

Transmission d'informations



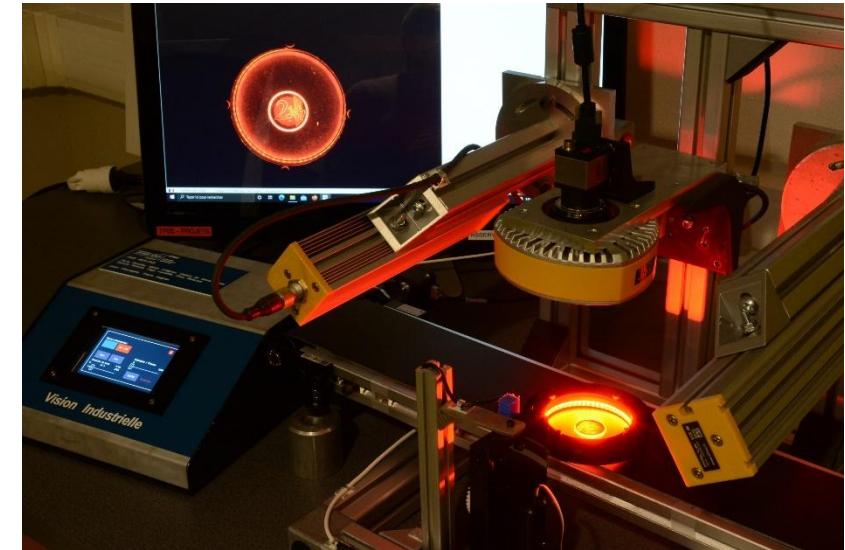
Modification des propriétés de la lumière pour porter une information

- Polarisation
- Amplitude (modulation)
- Phase
- Intrication

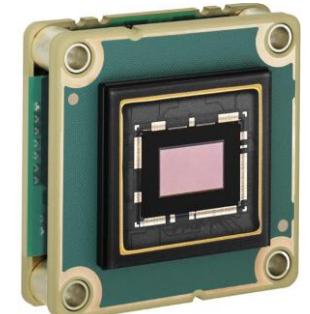


Photodétection / Exemples

Application de la photodétection



IDS Sensor

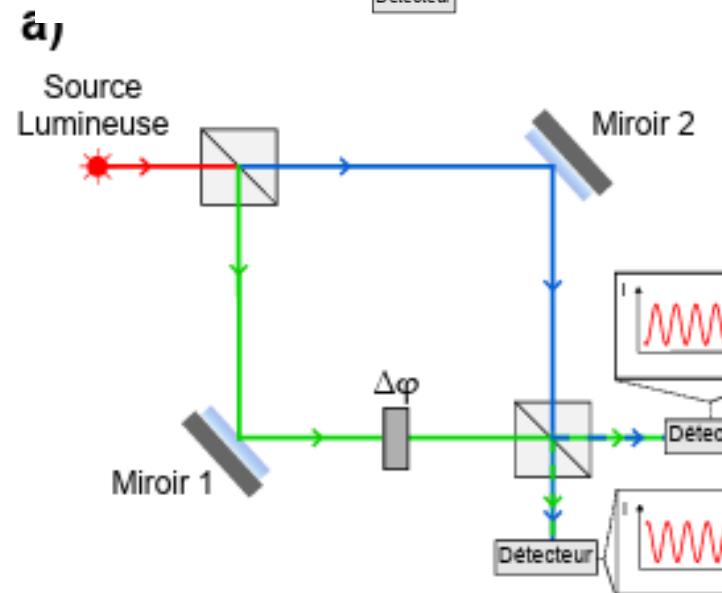
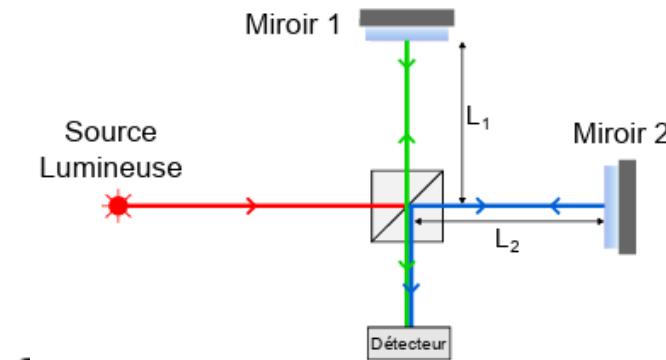


Basler Sensor / Mouser

Photodétection / Exemples

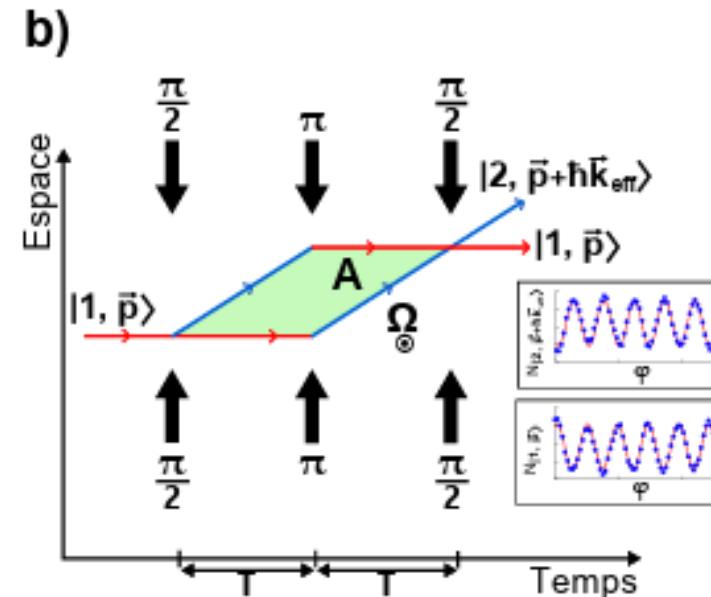
Applications en photonique

Représentation d'un interféromètre de **Michelson**



Interféromètre à atomes froids piégés sur puce avec séparation spatiale

Groupe Gaz Quantiques / LCF

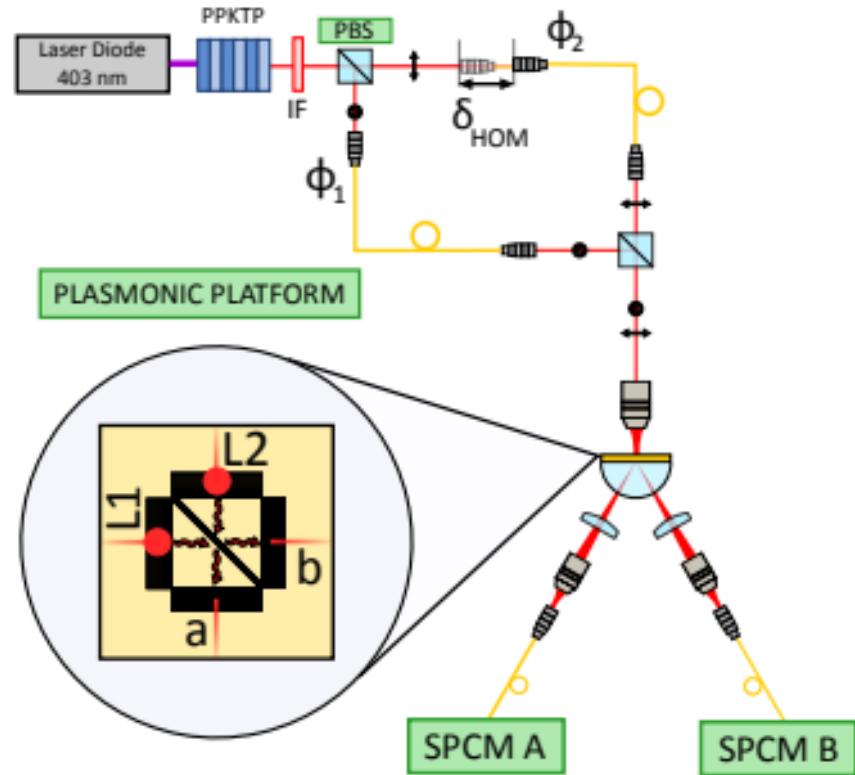


Représentation d'un interféromètre de **Mach-Zehnder** (a) en optique, et (b) en version atomique, aussi appelé Ramsey-Bordé.

Photodétection / Exemples

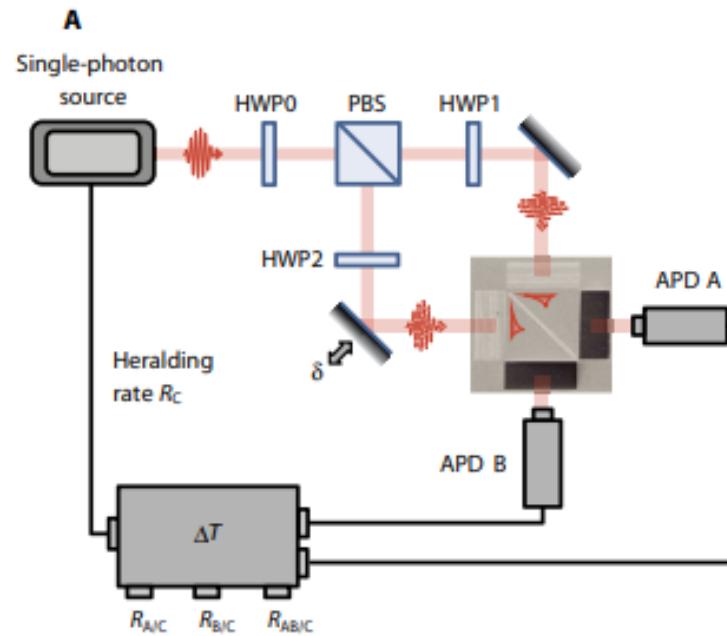
Applications en photonique

Anti-coalescence of bosons on a lossy beamsplitter



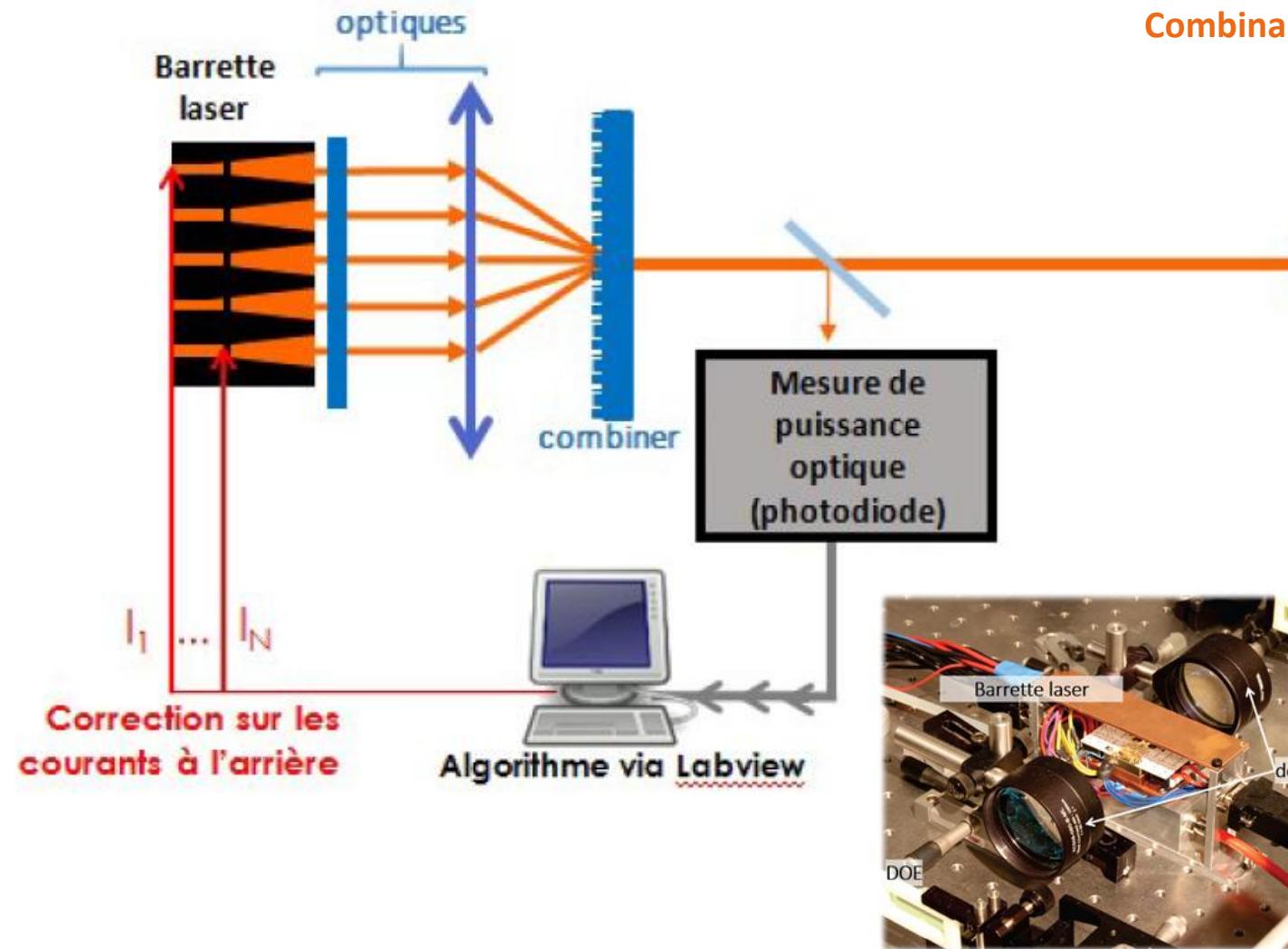
Single-plasmon interferences

Groupe Nanophotonique / LCF



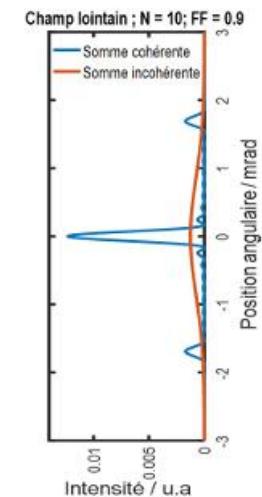
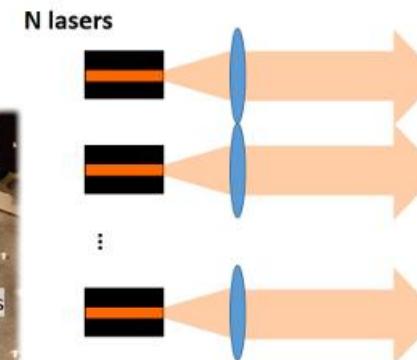
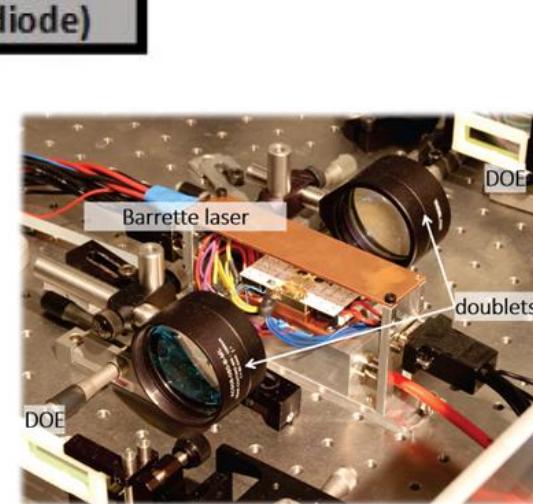
Photodétection / Exemples

Applications en photonique



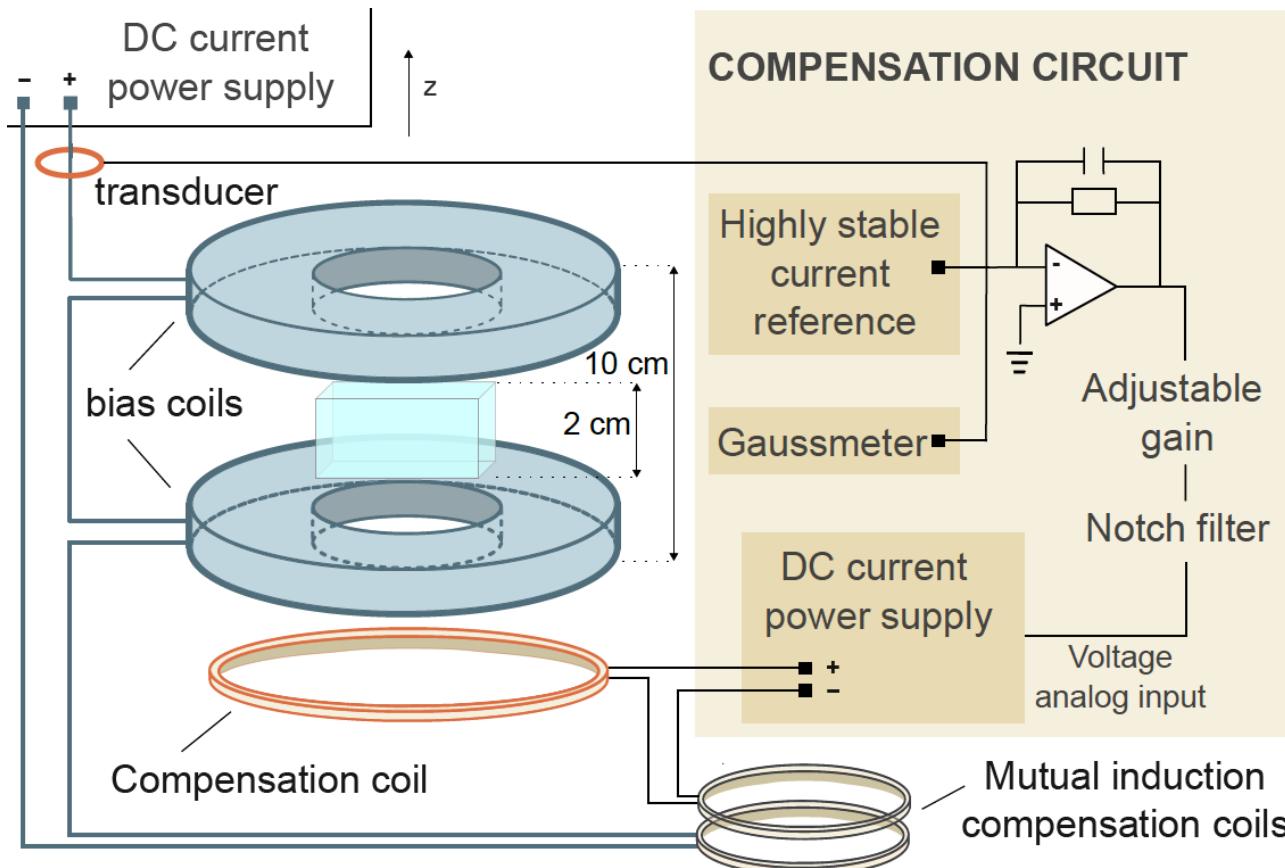
Combinaison cohérente de diodes laser de puissance

Groupe Laser / LCF



Electronique / Exemples

Applications en photonique



Magnetic field stabilisation for Bose-Einstein condensation experiments

Groupe Gaz Quantique / LCF



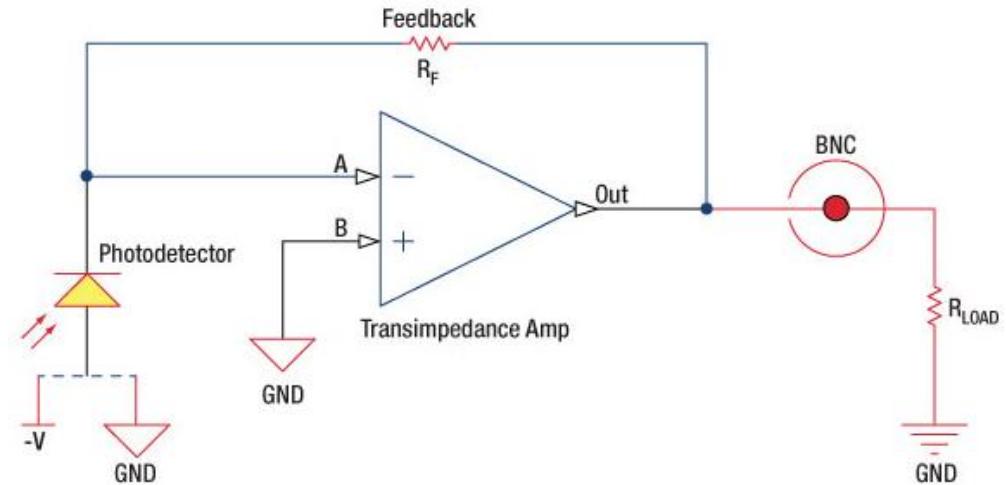
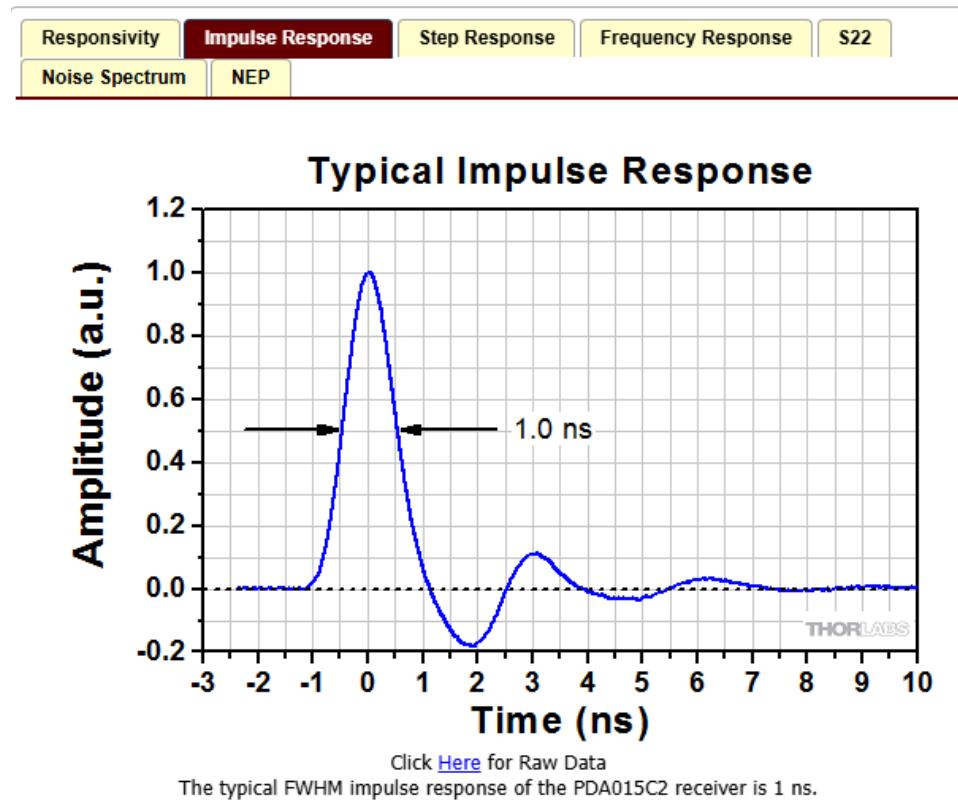
Schematic of the **stabilization system**. In essence, it is a **feedforward** technique in a separated coil. A key feature is that the mutual inductance between the two circuits is cancelled.

Photodétection / Exemples

Applications en photonique



PDA015C2 - InGaAs Fixed Gain Amplified Detector, 800 - 1700 nm, 380 MHz BW, 0.018mm², + Universal 8-32 / M4 Mounting Holes



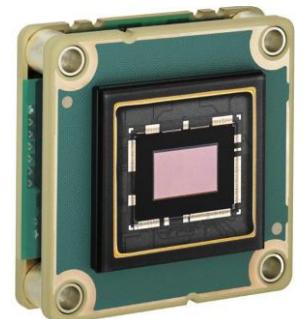
THORLABS

Photodétection

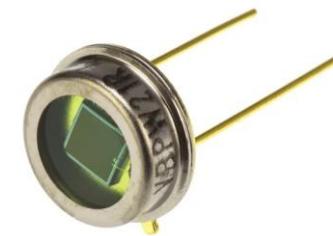
Définition et chaîne d'acquisition



IDS Sensor



Basler Sensor / Mouser

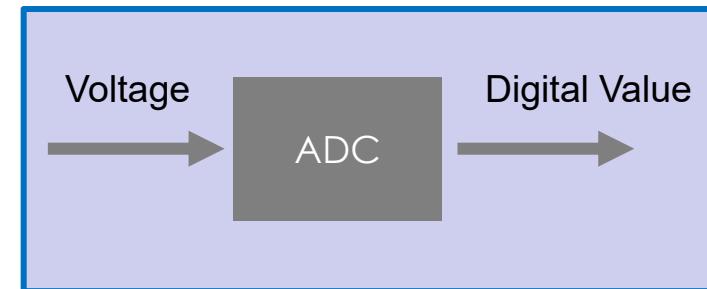
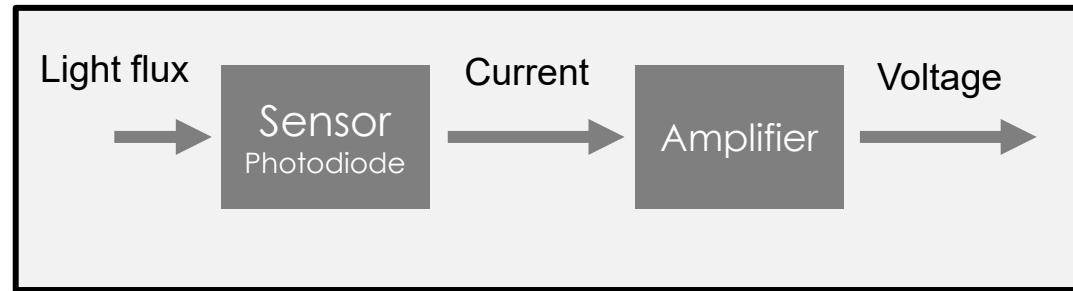


Photodétection

Système de photodétection

Système de photodétection

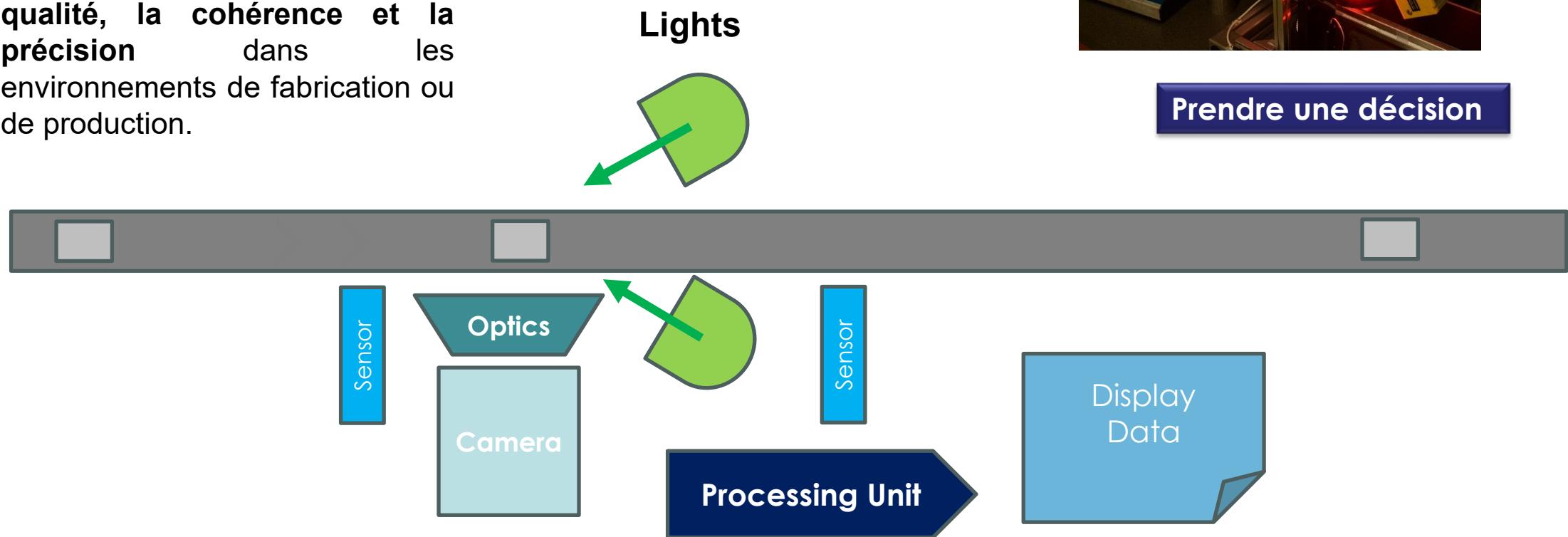
Convertir un signal lumineux
(flux de photons) en un signal électrique mesurable



Système de photodétection

Système de vision industrielle

Automatiser le **processus d'inspection des produits** ou des matériaux afin de **garantir la qualité, la cohérence et la précision** dans les environnements de fabrication ou de production.



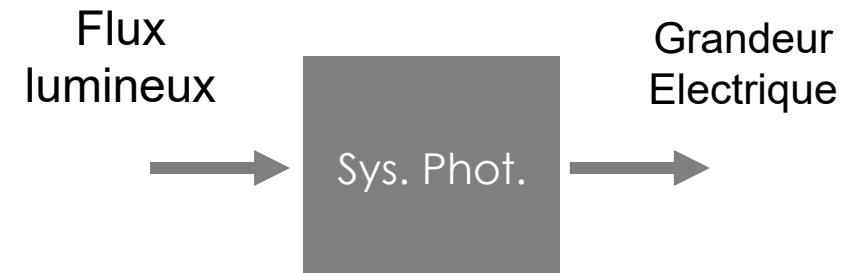
Photodétection

Système de phot. / Caractéristiques

- **Sensibilité** : rapport entre le courant de sortie et la puissance optique incidente
- **Bruit** : fluctuations indésirables du signal électrique
 - *Bruit d'amplification*
 - *Bruit thermique (Johnson-Nyquist)*
 - *Bruit de photons*
- **Rapport signal à bruit** : mesure la qualité du signal détecté
- **Temps de réponse** : durée nécessaire pour que le signal atteigne un niveau stable après une variation
- **Bandé passante** : fréquence maximale de modulation détectable
- **Courant d'obscurité** : courant généré par le détecteur en l'absence de lumière
- **Stabilité et linéarité**

Système de photodétection

Convertir un signal lumineux (flux de photons) en un signal électrique mesurable



Photodétection

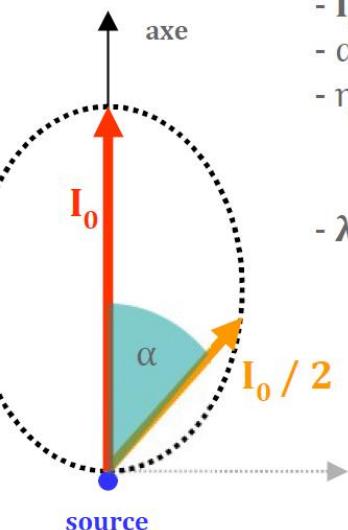
Système de phot. / Caractéristiques

- **Bandes spectrales de réponse** : domaine de longueurs d'onde pour lesquelles le détecteur est sensible
- **Efficacité quantique** : fraction de photons incidents qui génèrent effectivement un électron
- **Taille active** : détermine la quantité de lumière collectée

Système de photodétection

Convertir un signal lumineux (flux de photons) en un signal électrique mesurable

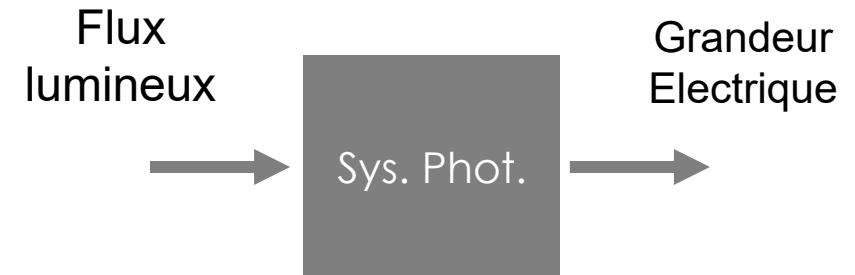
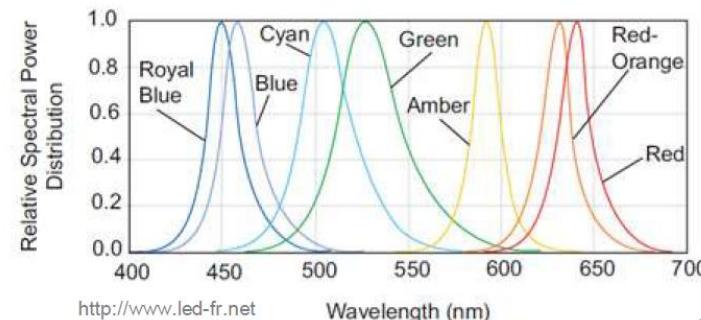
CARACTÉRISTIQUES OPTIQUES



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

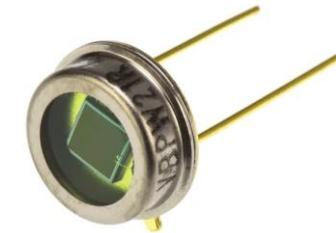
$$\eta = \frac{\text{Nb photons émis}}{\text{Nb électrons}}$$

- λ : longueur d'onde d'émission

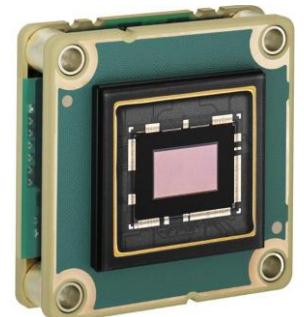


LEDs / Photodiodes

Caractéristiques des diodes



IDS Sensor

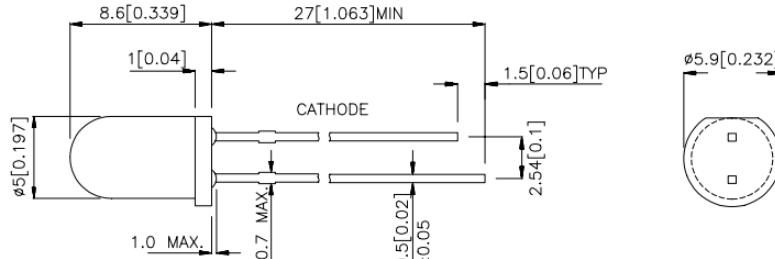


Basler Sensor / Mouser

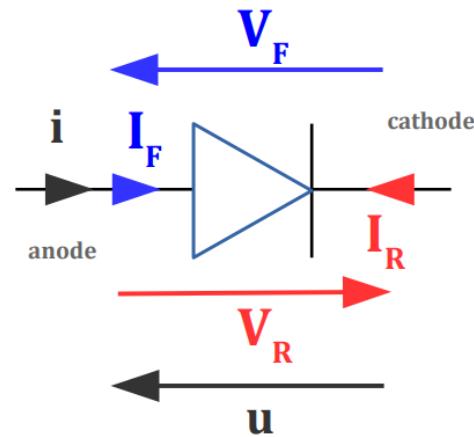
Caractéristique statique

Diode

Dipôle non linéaire et polarisé



DIODE



I_F : courant direct

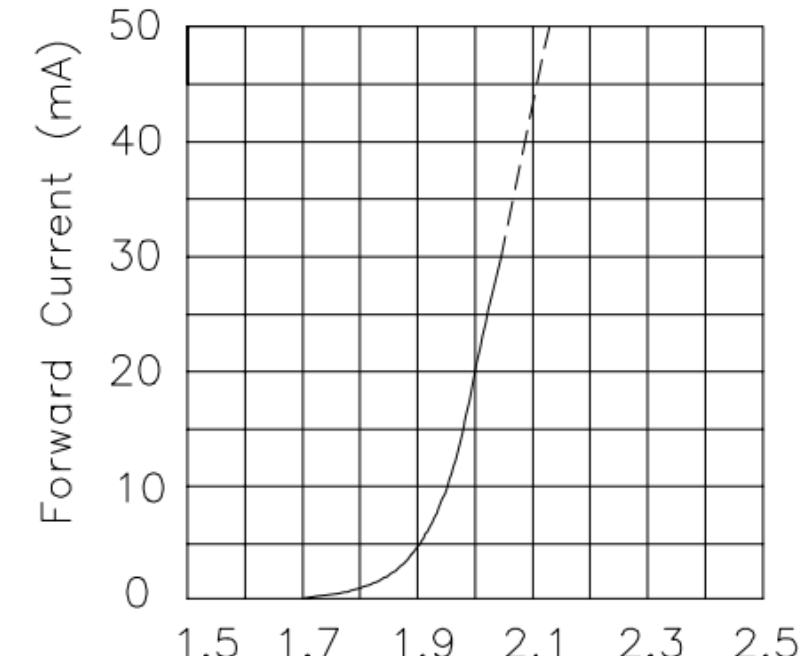
souvent $I_F < I_{FMAX}$

V_F : tension directe

aussi appelée seuil

I_R : courant inverse

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

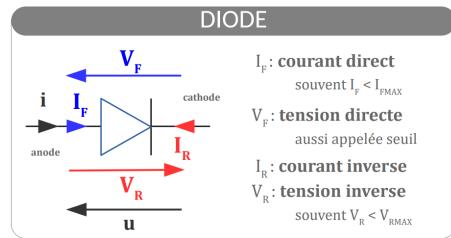


Forward Voltage(V)
FORWARD CURRENT Vs.
FORWARD VOLTAGE

Caractéristique statique

Diode

Dipôle non linéaire et polarisé



MODÈLE COMPLET

Si $u > 0$, diode passante

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

loi exponentielle

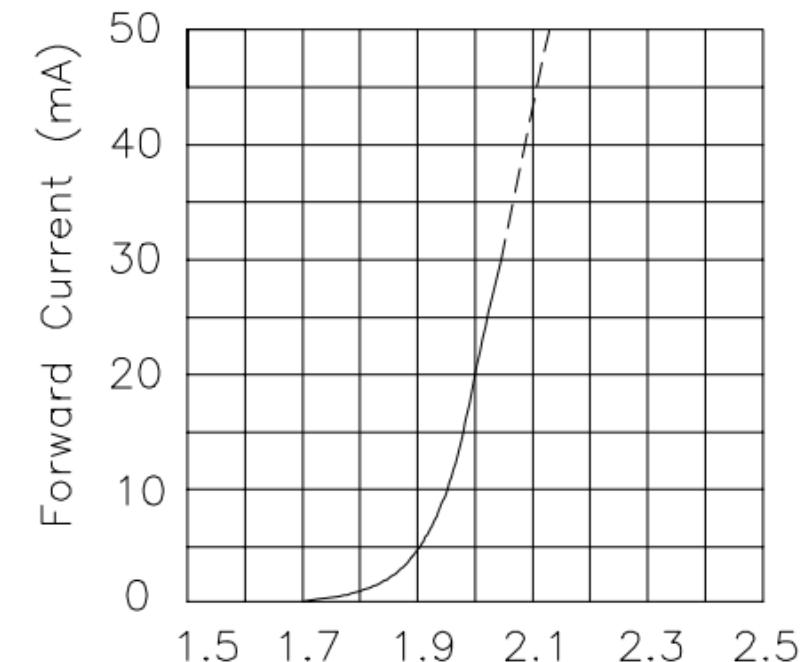
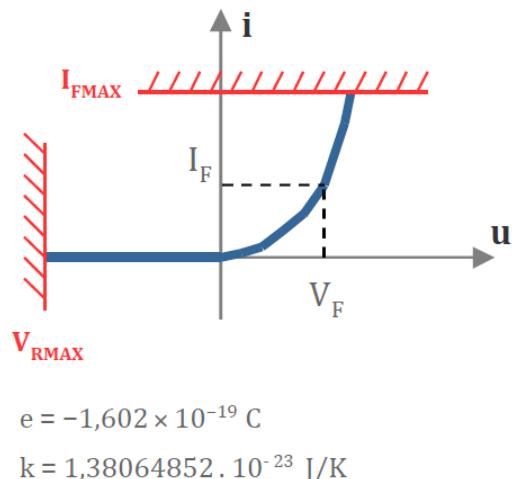
V_0 : tension thermique

$$V_0 = k.T / e$$

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

n : facteur de qualité

I_0 : constante spécifique à un type

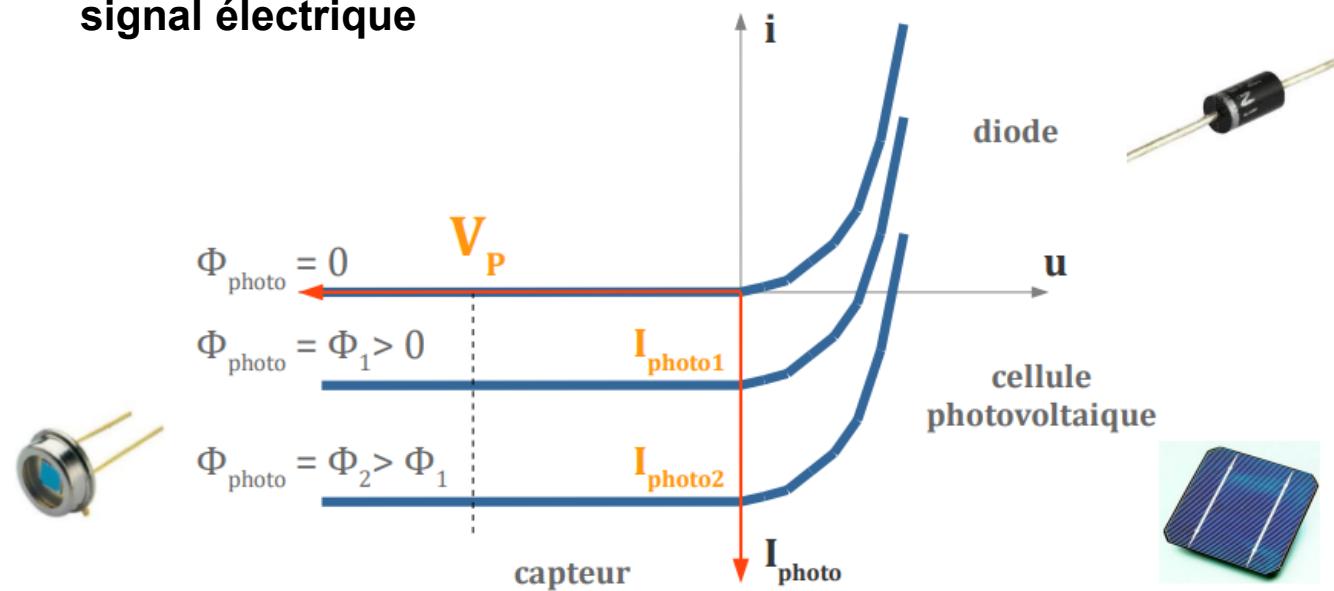


High Efficiency Red L-53ID

Caractéristique statique

Photodiode

Dipôle non linéaire et polarisé, ayant la capacité de capter un rayonnement du domaine optique et de le transformer en signal électrique

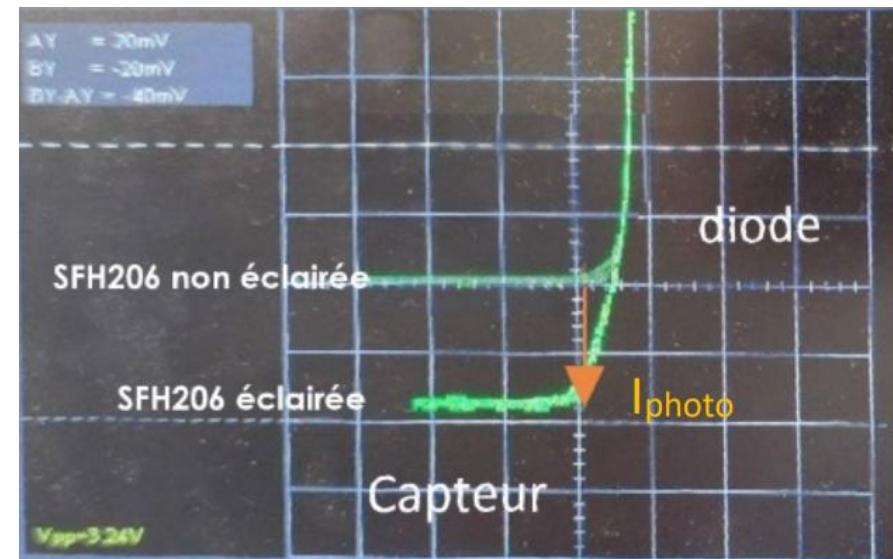


$$I = I_0 \left[\exp \left(\frac{V_j}{nV_0} \right) - 1 \right]$$

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

Diagram illustrating the formula for photocurrent:

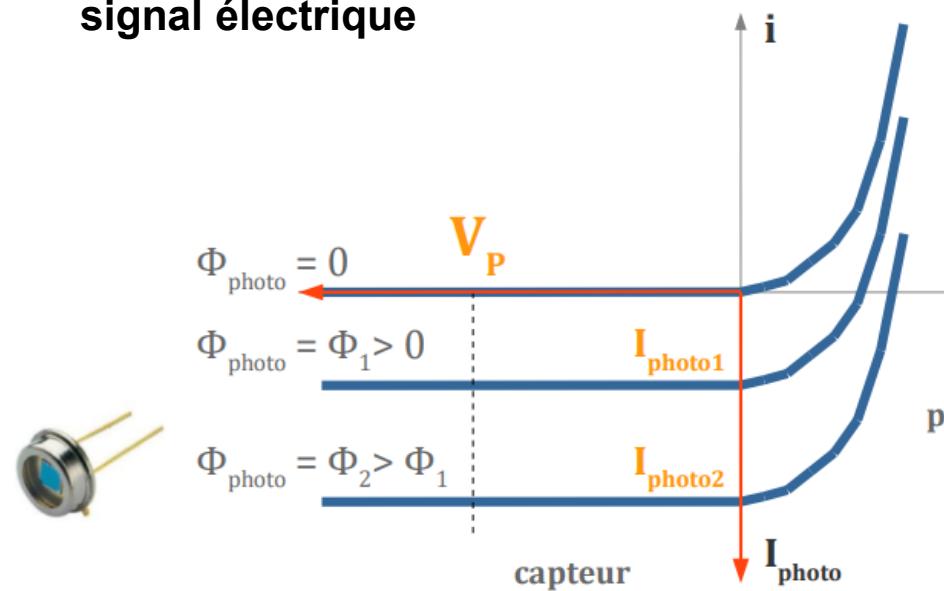
- A:** Sensibilité spectrale (Spectral sensitivity)
- A/W:** Flux lumineux (Luminous flux)
- W:** Rendement quantique (Quantum yield)



Caractéristique statique

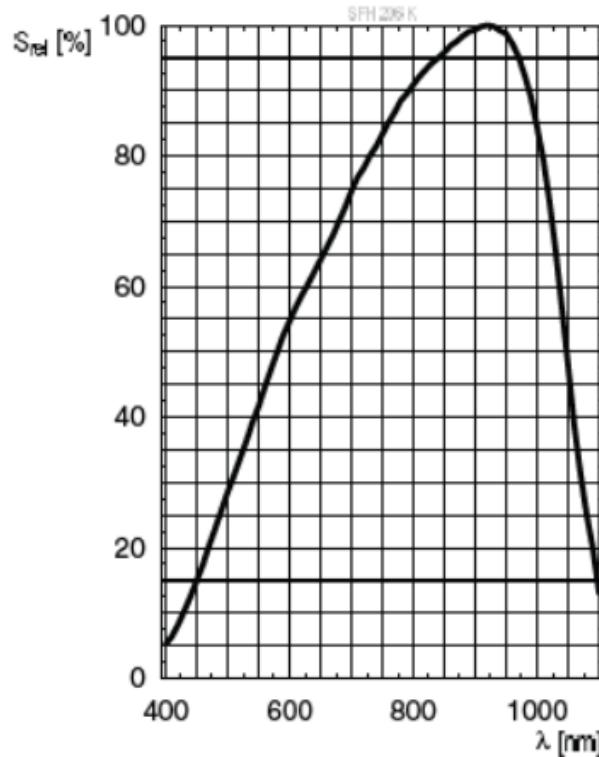
Photodiode

Dipôle non linéaire et polarisé, ayant la capacité de capter un rayonnement du domaine optique et de le transformer en signal électrique



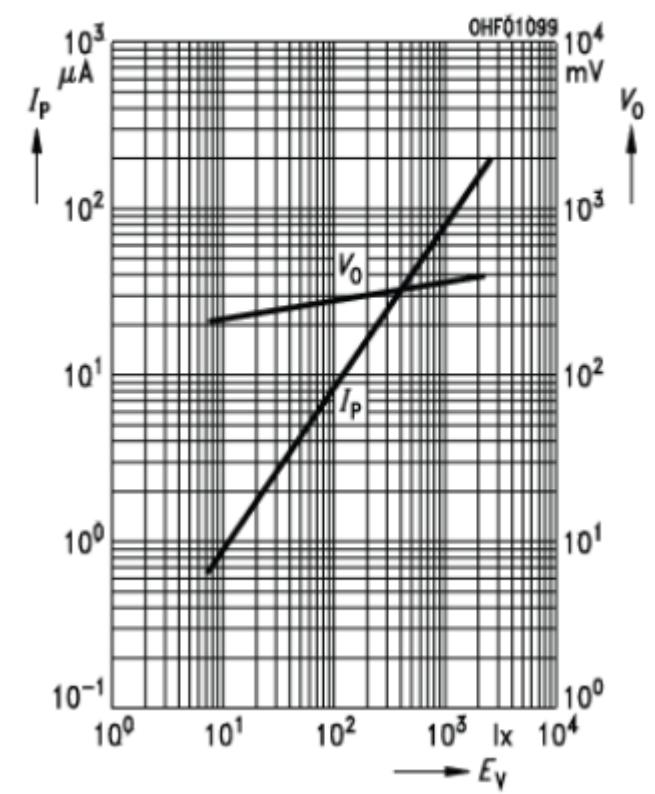
SFH 206 K

Relative Spectral Sensitivity



Photocurrent/Open-Circuit Voltage

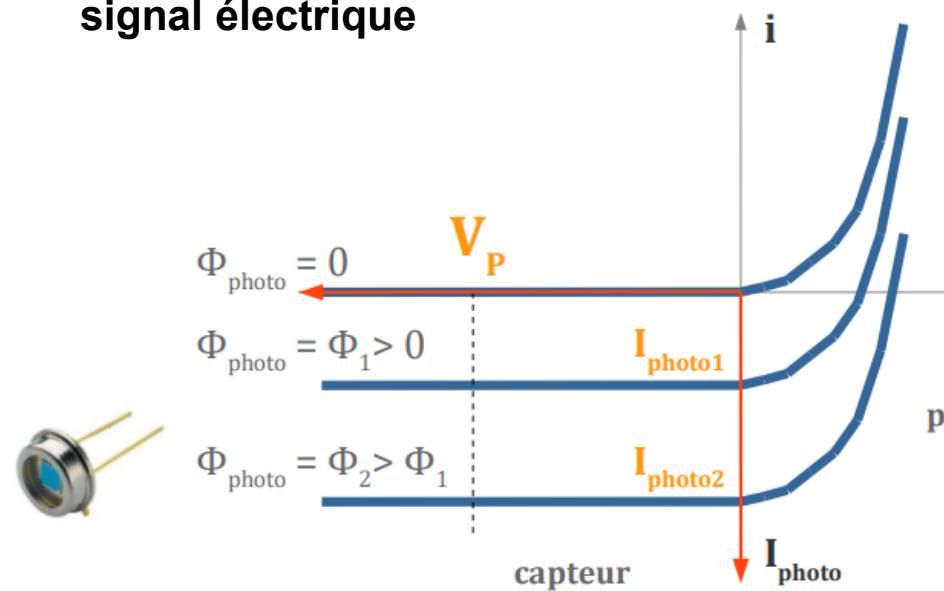
$$I_P (V_R = 5 \text{ V}) / V_O = f(E_V)$$



Caractéristique statique

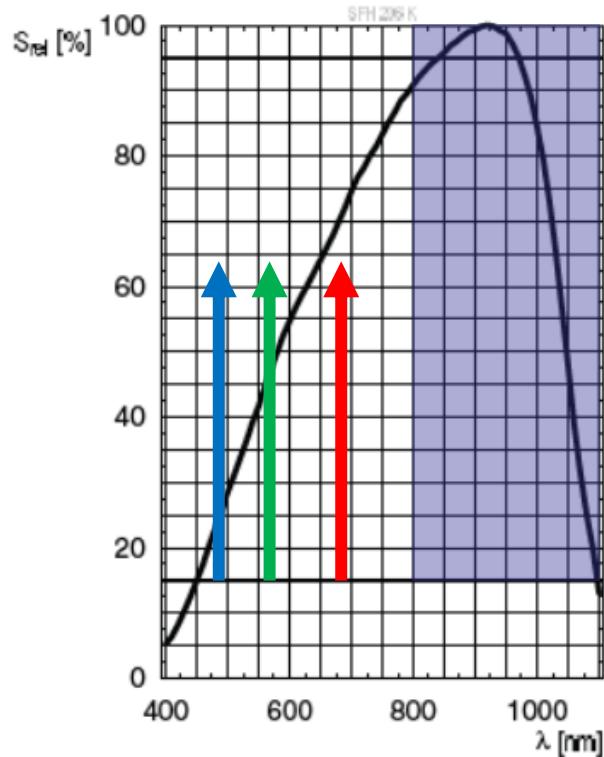
Photodiode

Dipôle non linéaire et polarisé, ayant la capacité de capter un rayonnement du domaine optique et de le transformer en signal électrique



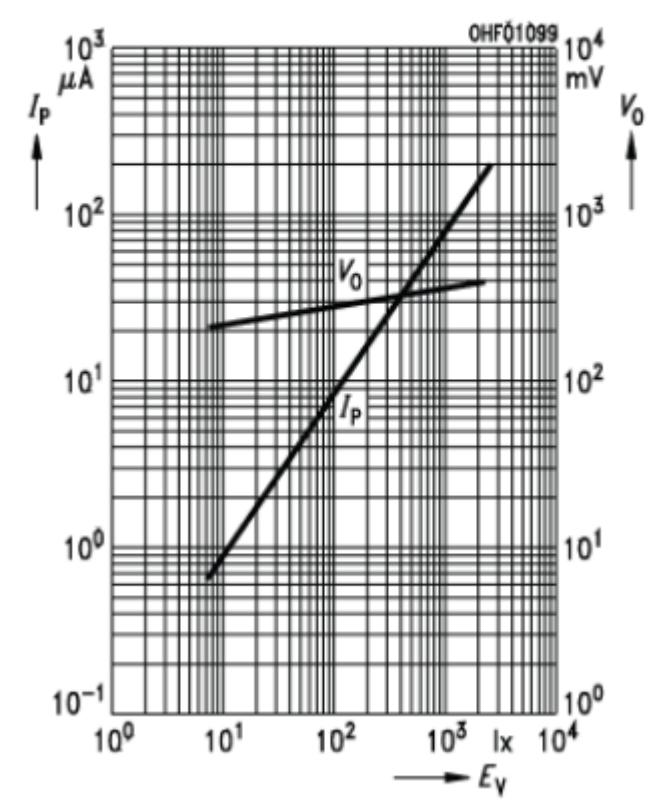
SFH 206 K

Relative Spectral Sensitivity



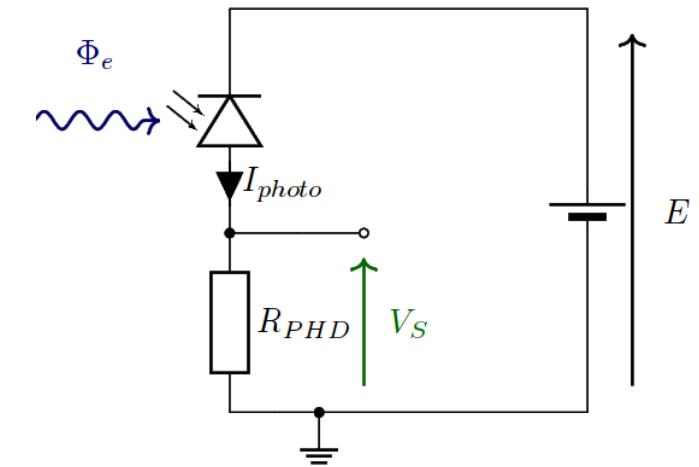
Photocurrent/Open-Circuit Voltage

$$I_P (V_R = 5 \text{ V}) / V_O = f(E_V)$$

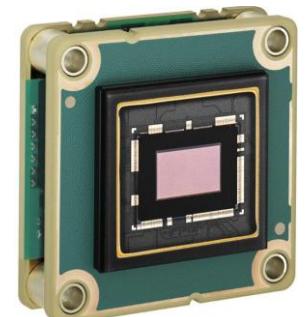


Montage de photodétection

Montage « simple »



IDS Sensor



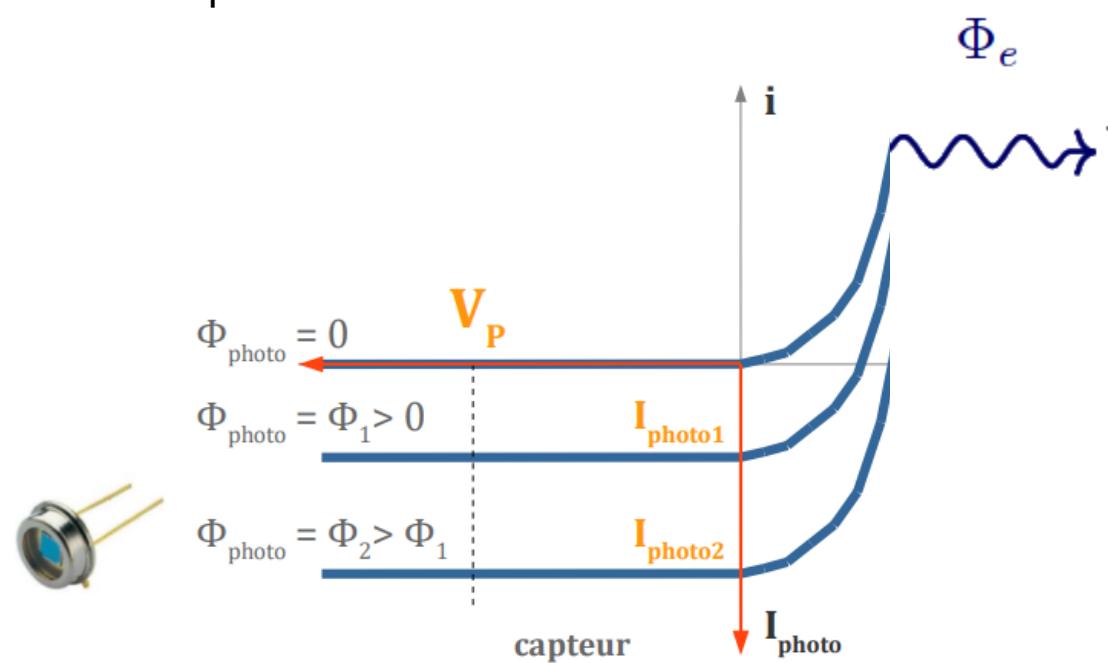
Basler Sensor / Mouser

Système de photodétection

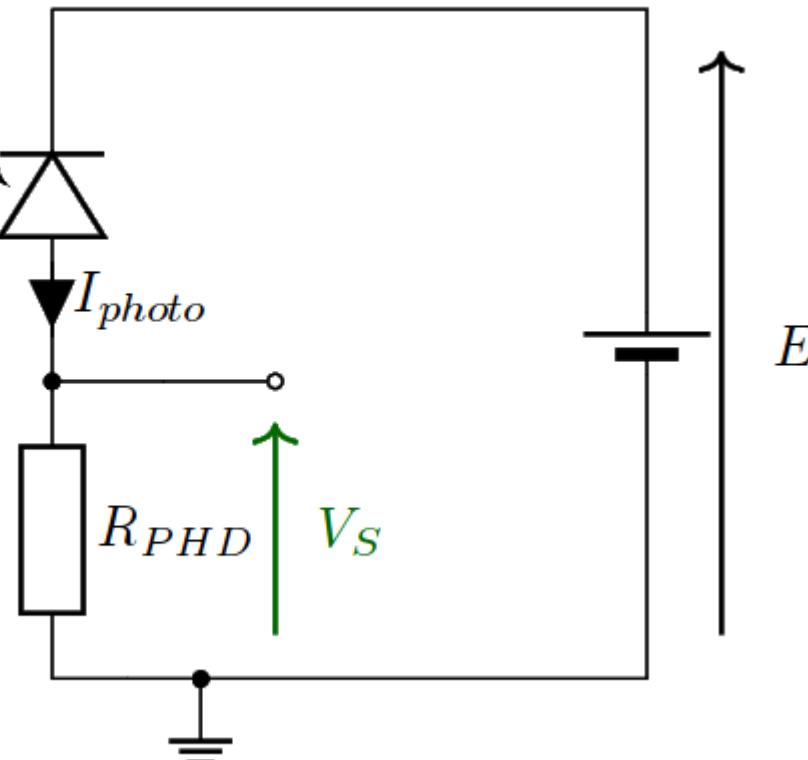
Version « simple »

Montage de photodétection

Convertir un signal lumineux
(flux de photons) en un signal
électrique mesurable



$$V_s = R_{PHD} \cdot I_{photo} = R_{PHD} \cdot k \cdot \Phi_e$$

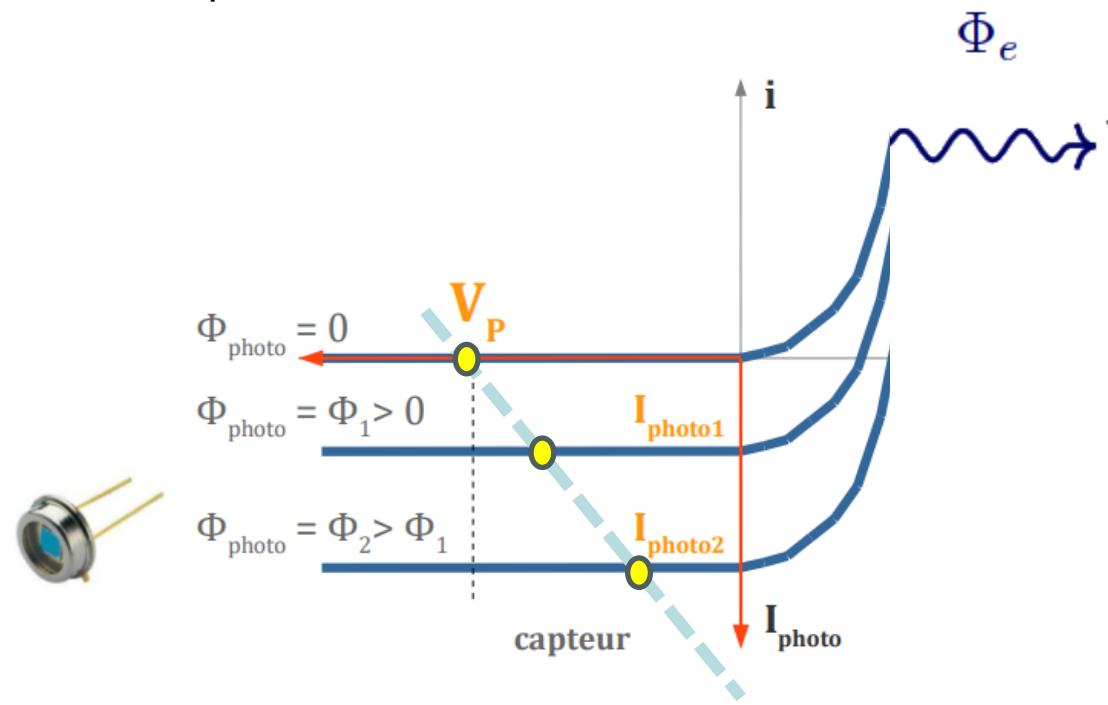


Système de photodétection

Version « simple »

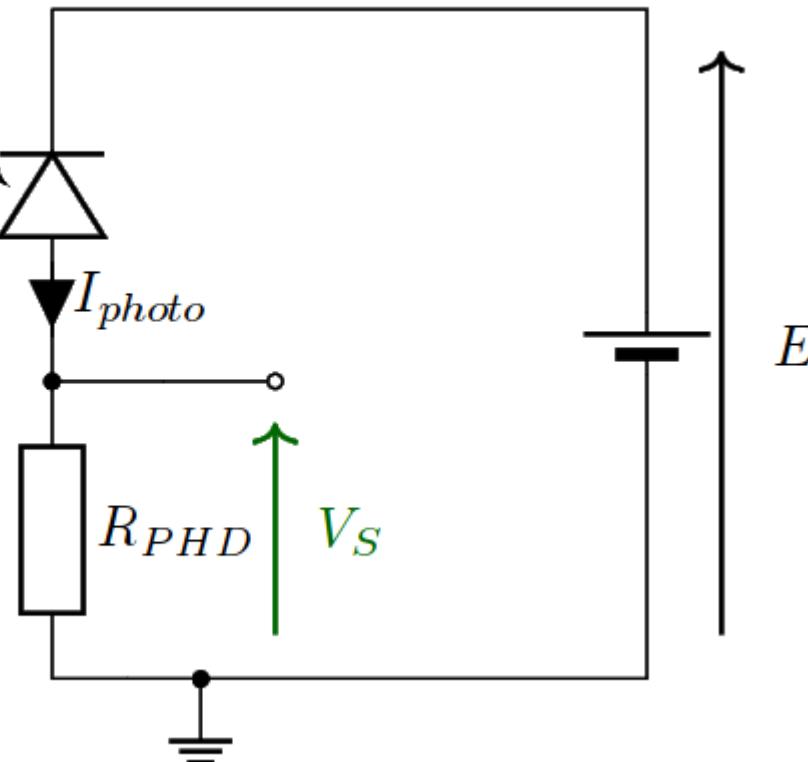
Montage de photodétection

Convertir un signal lumineux
(flux de photons) en un signal
électrique mesurable



$$V_s = R_{PHD} \cdot I_{photo} = R_{PHD} \cdot k \cdot \Phi_e$$

Tension de polarisation non constante

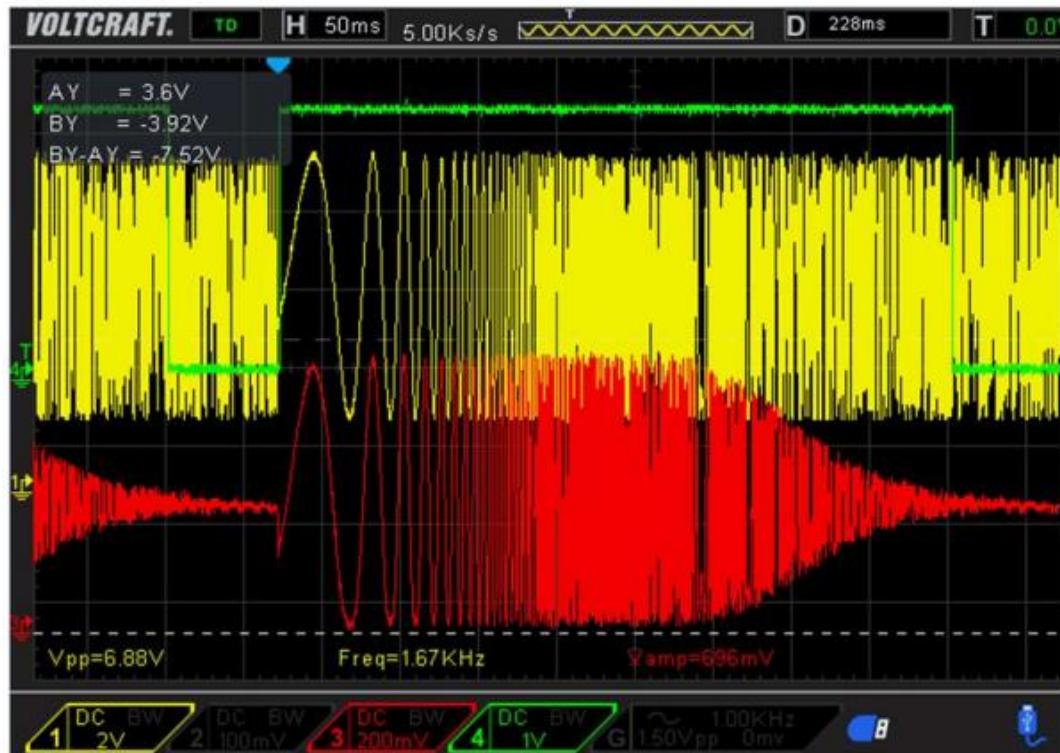


Système de photodétection

Version « simple » / En pratique

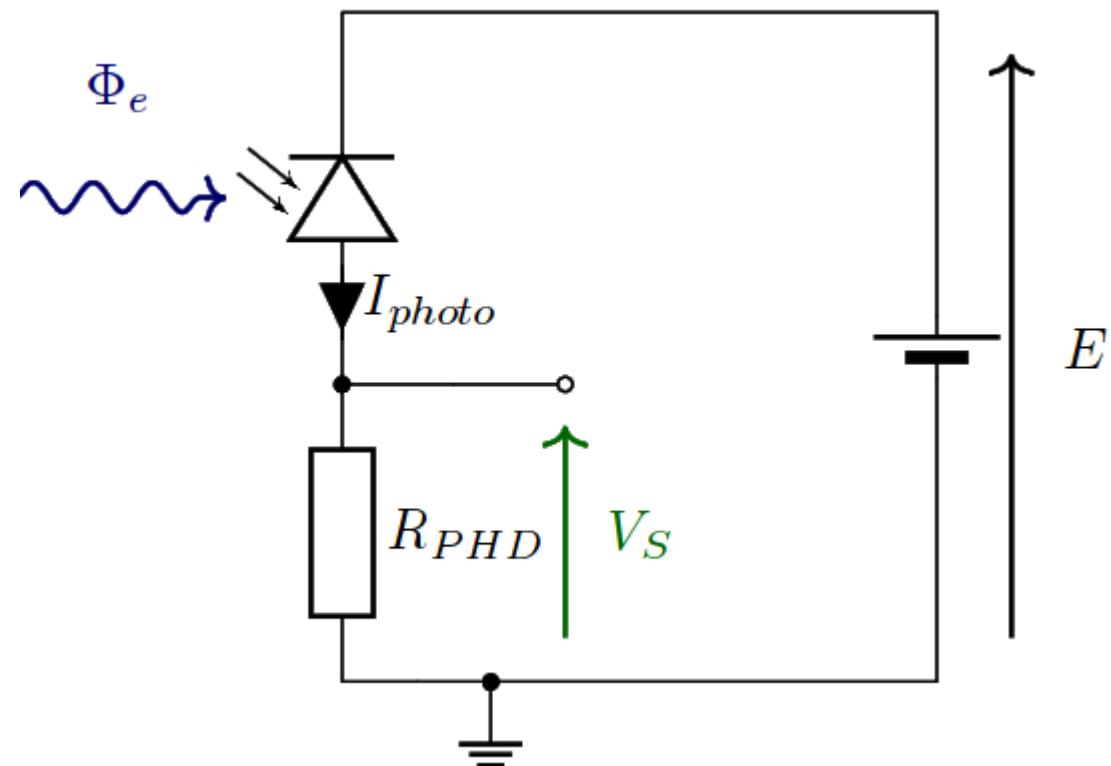
Montage de photodétection

Convertir un signal lumineux
(flux de photons) en un signal électrique mesurable



$$V_s = R_{PHD} \cdot I_{photo} = R_{PHD} \cdot k \cdot \Phi_e$$

MODELE NON VALIDE !!

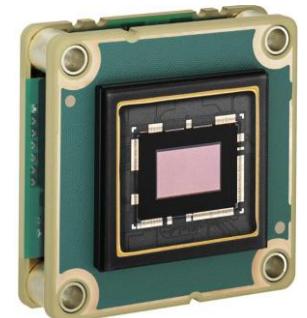


LEDs

Caractéristiques



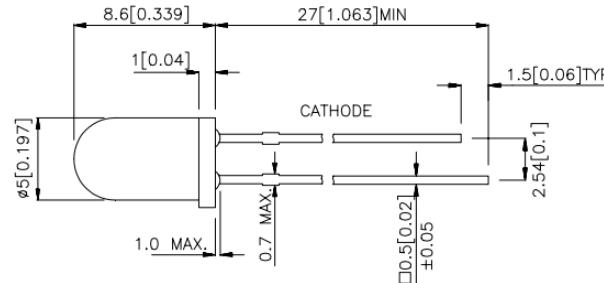
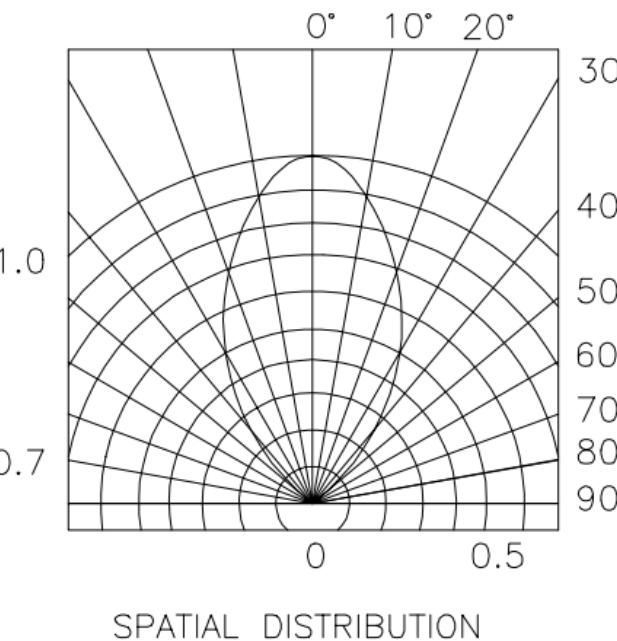
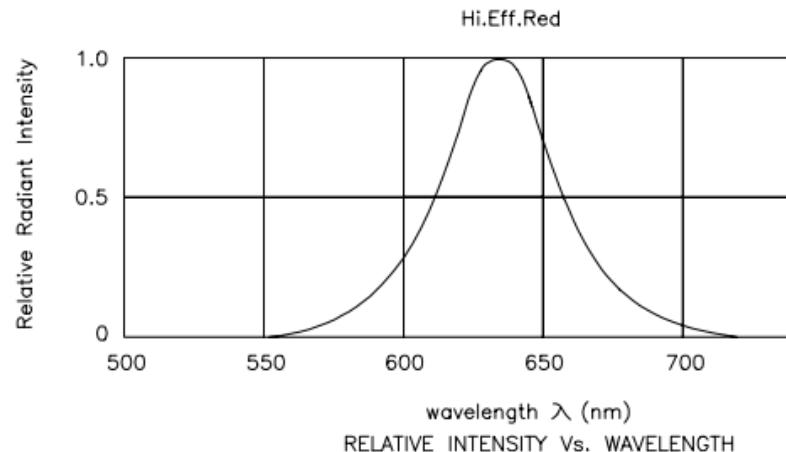
IDS Sensor



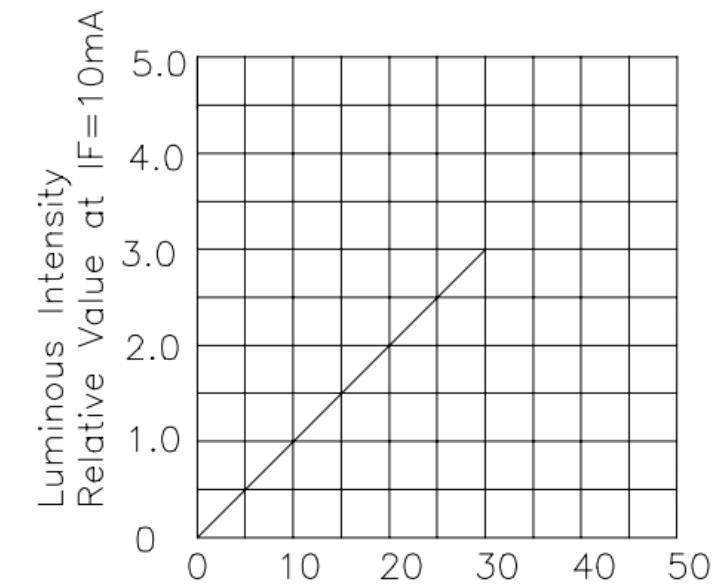
Basler Sensor / Mouser

LED

Dipôle non linéaire et polarisé capable d'émettre de la lumière lorsqu'il est parcouru par un courant électrique



Caractéristique statique



If – Forward Current (mA)
LUMINOUS INTENSITY Vs.
FORWARD CURRENT

High Efficiency Red L-53ID

Utilisation et limites d'utilisation

LED

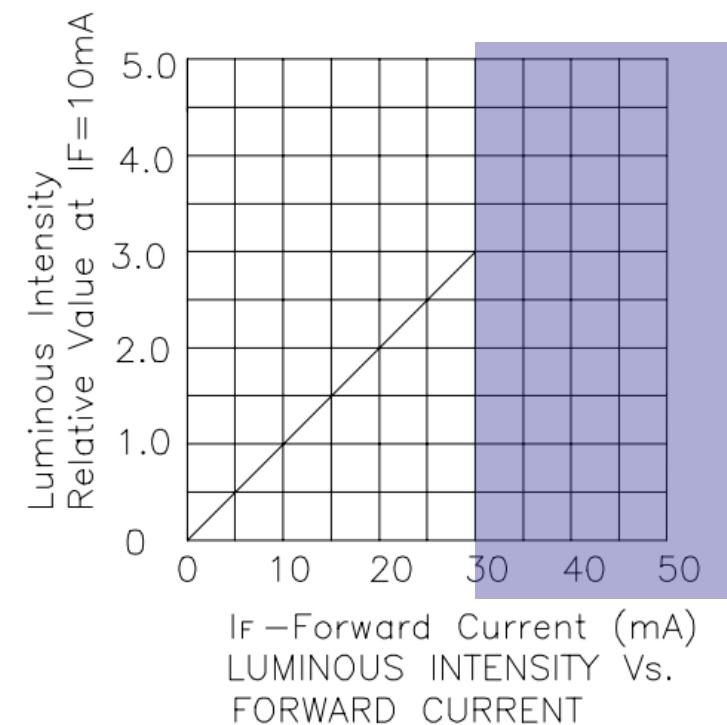
Absolute Maximum Ratings at $T_A=25^\circ\text{C}$

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.

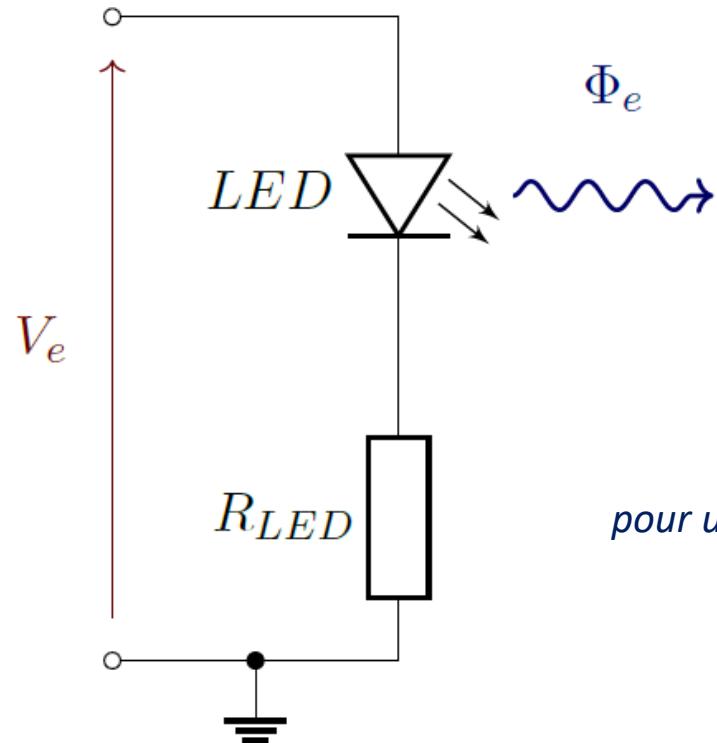


Kingbright

High Efficiency Red L-53ID

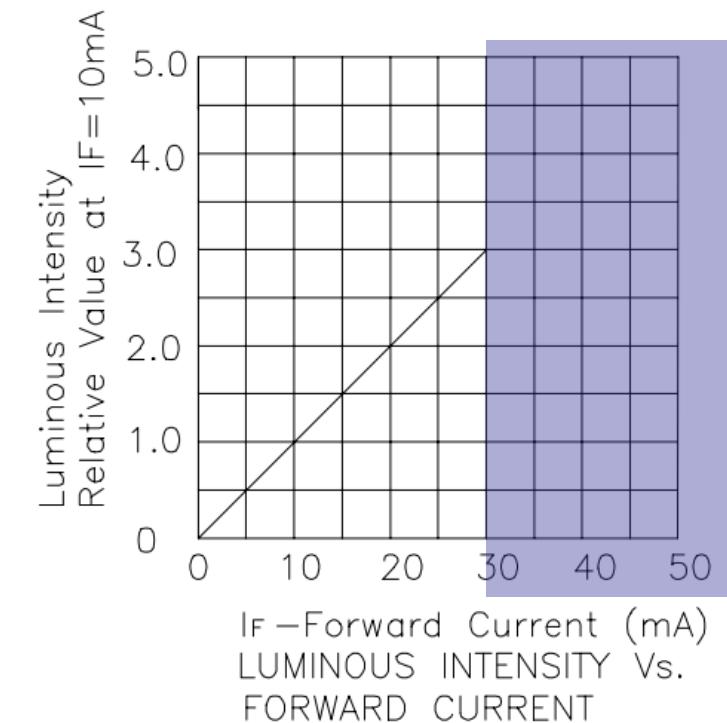
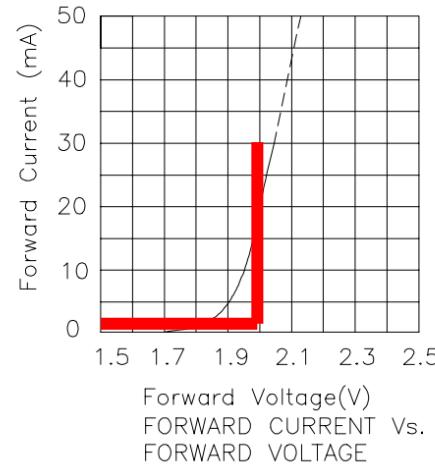
Utilisation et limites d'utilisation

LED



$$V_f = 2V$$

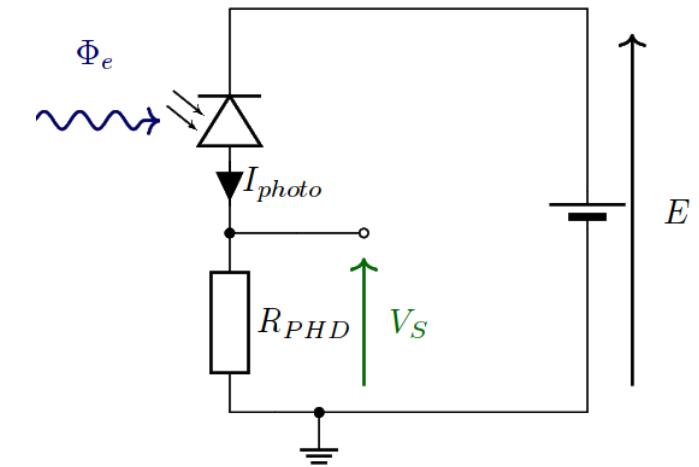
$$I_{f_{MAX}} = 30 \text{ mA}$$



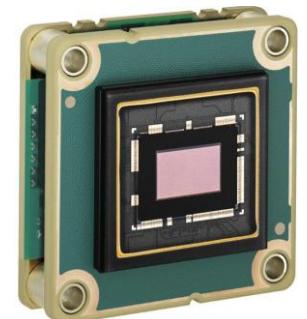
High Efficiency Red L-53ID

Montage de photodétection

Montage « simple » et modélisation



IDS Sensor



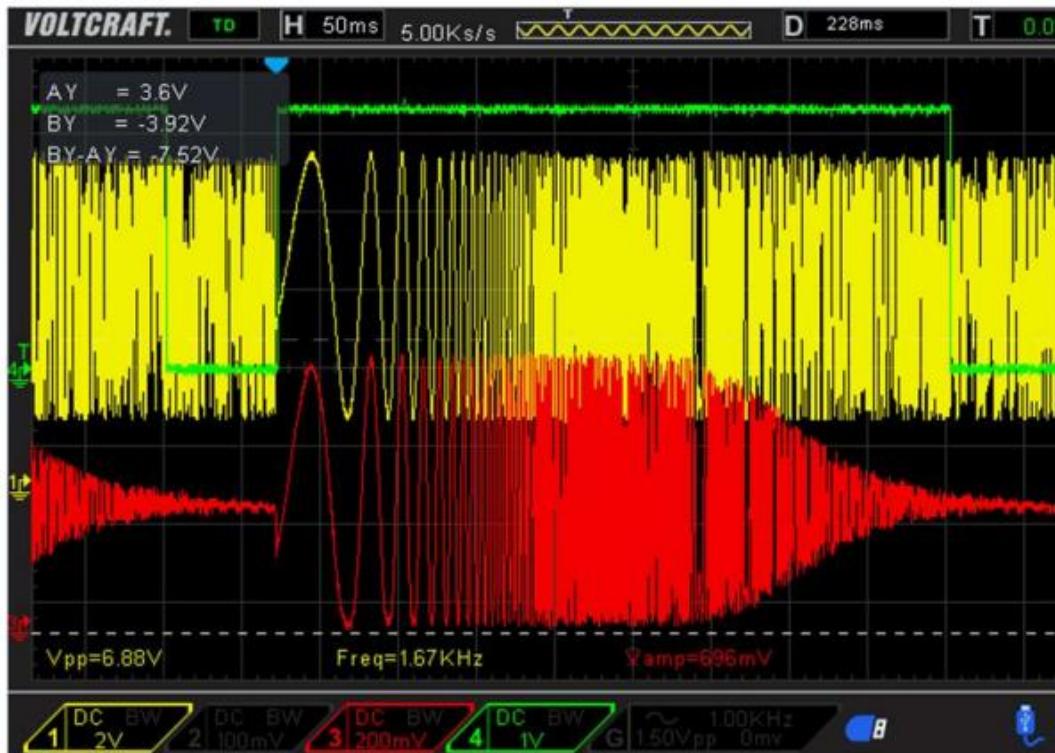
Basler Sensor / Mouser

Système de photodétection

Version « simple » / En pratique

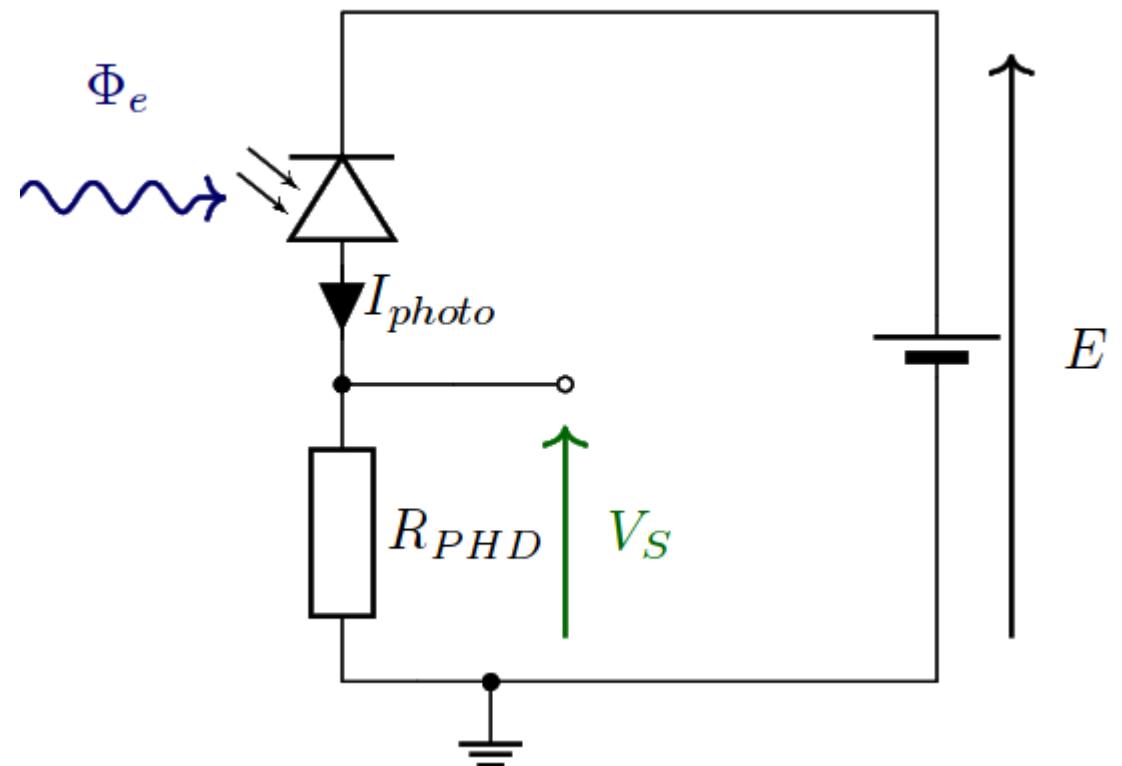
Montage de photodétection

Convertir un signal lumineux
(flux de photons) en un signal électrique mesurable



$$V_s = R_{PHD} \cdot I_{photo} = R_{PHD} \cdot k \cdot \Phi_e$$

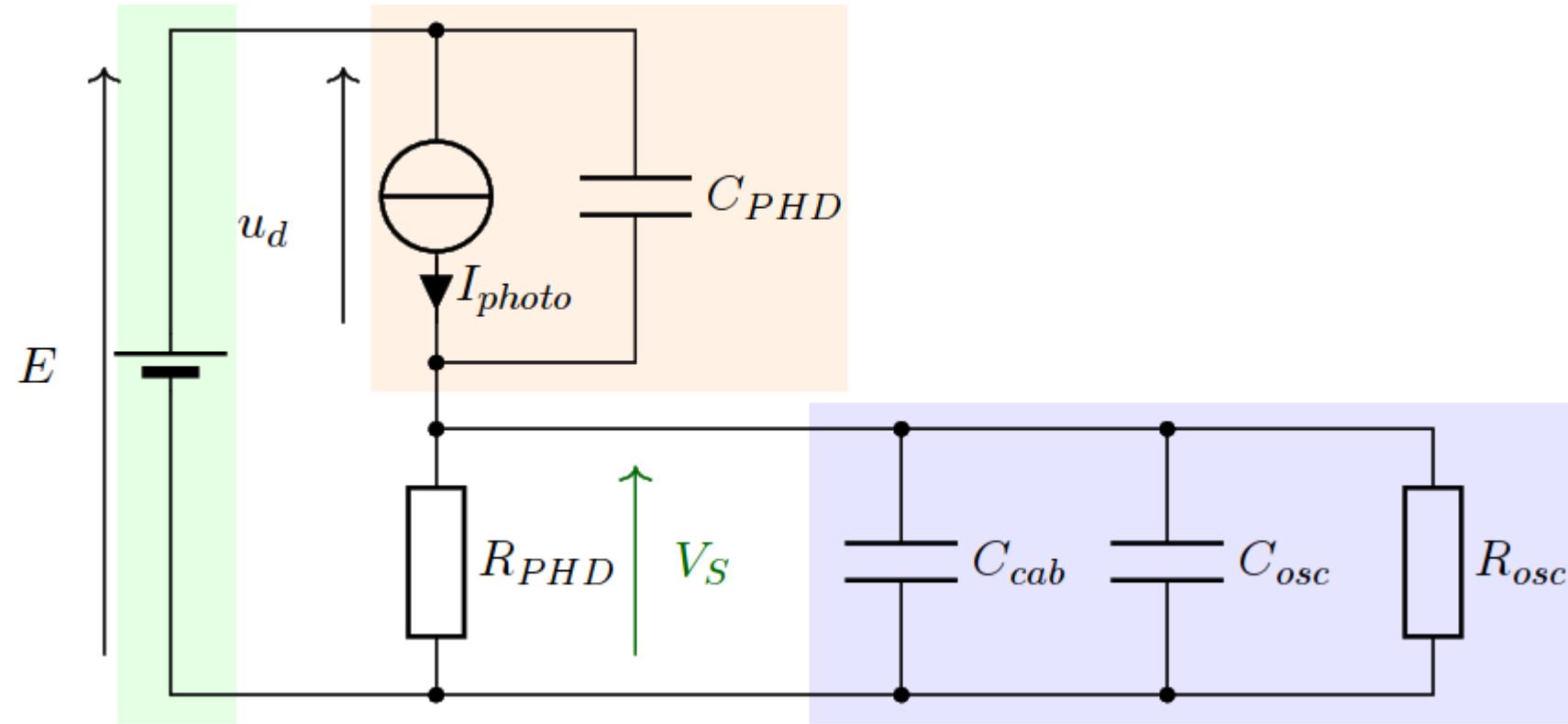
MODELE NON VALIDE !!



Système de photodétection

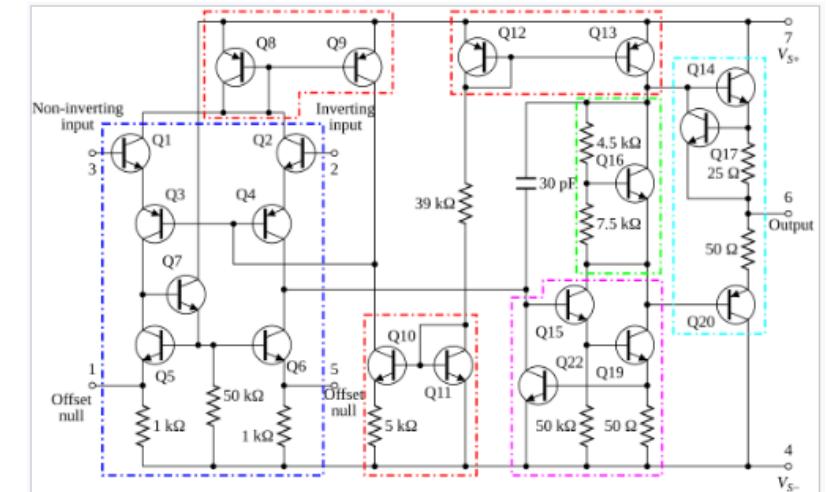
Version « simple » / Modélisation

Modélisation



Amplificateur linéaire

Adaptation d'impédance et transimpédance

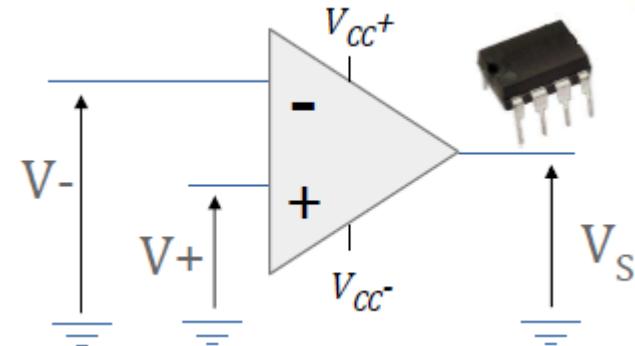


Amplificateur Linéaire Intégré

Fonction de transfert / Caractéristiques

ALI / AOP

Composant actif, **amplificateur différentiel** à grand gain



FONCTION DE TRANSFERT

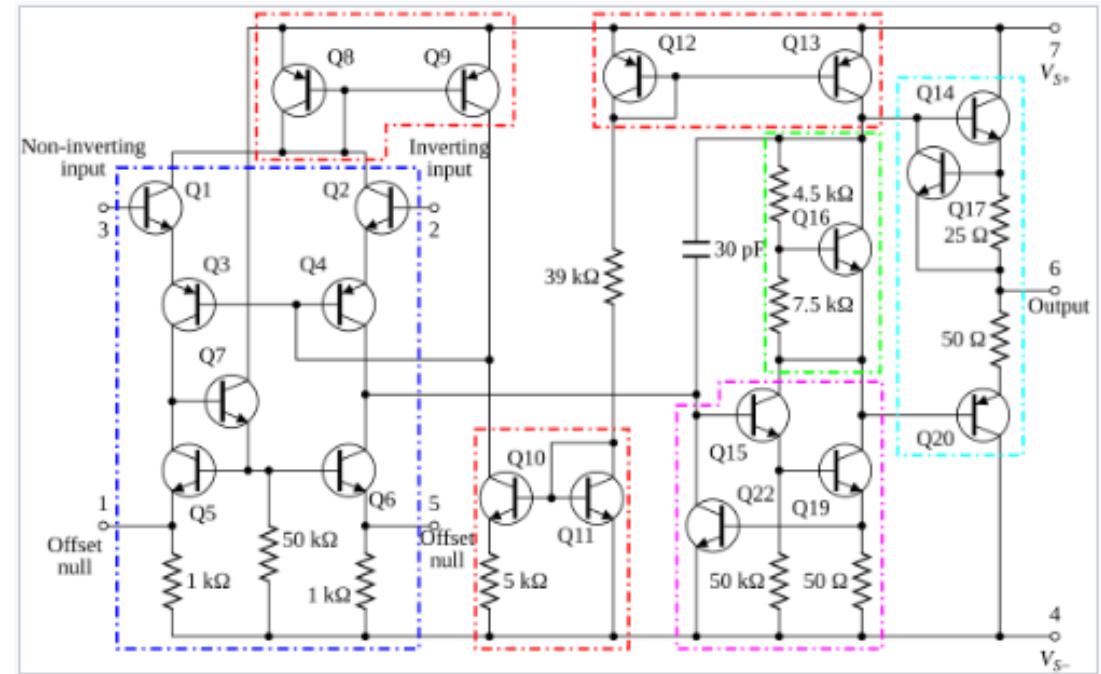
$$V_S = A \cdot (V_+ - V_-)$$

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

Saturation à $V_S = V_{cc+}$

Impédance d'entrée élevée

► $i_+ = i_- = 0$

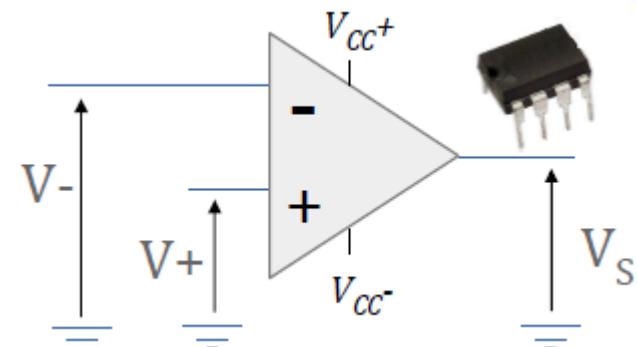


Amplificateur Linéaire Intégré

Fonction de transfert / Caractéristiques

ALI / AOP

Composant actif, **amplificateur différentiel** à grand gain



FONCTION DE TRANSFERT

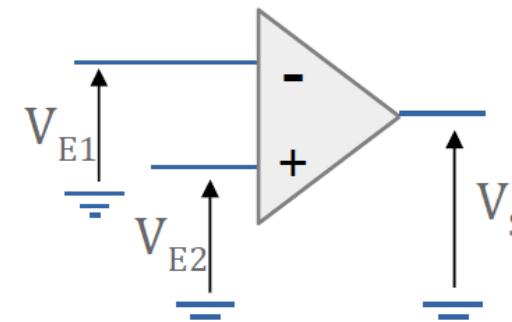
$$V_S = A \cdot (V_+ - V_-)$$

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

Saturation à $V_S = V_{cc+}$

Fonctionnement non-linéaire

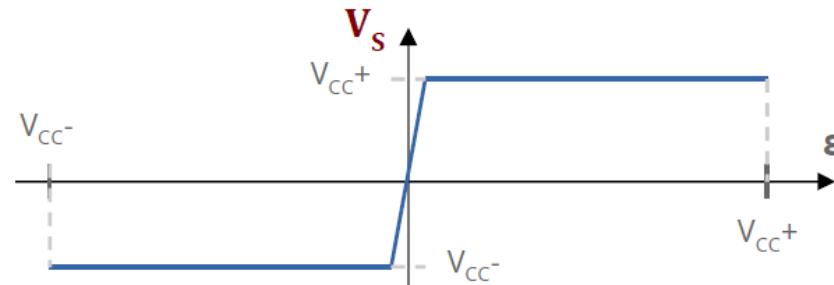
COMPARATEUR SIMPLE



$$V_S = V_{cc+} \quad \text{Si } V_{E2} > V_{E1}$$

$$V_S = V_{cc-} \quad \text{Si } V_{E1} > V_{E2}$$

Caractéristique $V_S = f(\varepsilon)$ avec $\varepsilon = V_+ - V_-$

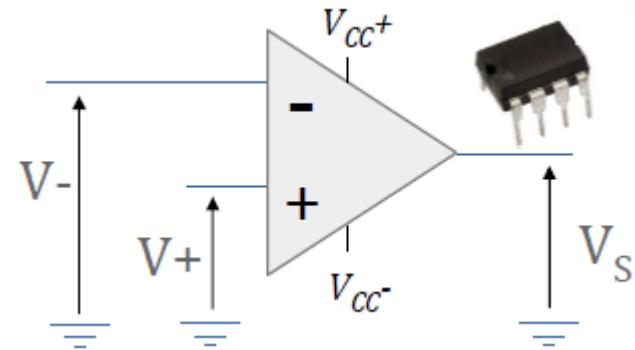


Amplificateur Linéaire Intégré

Fonction de transfert / Caractéristiques

ALI / AOP

Composant actif, **amplificateur différentiel** à grand gain



FONCTION DE TRANSFERT

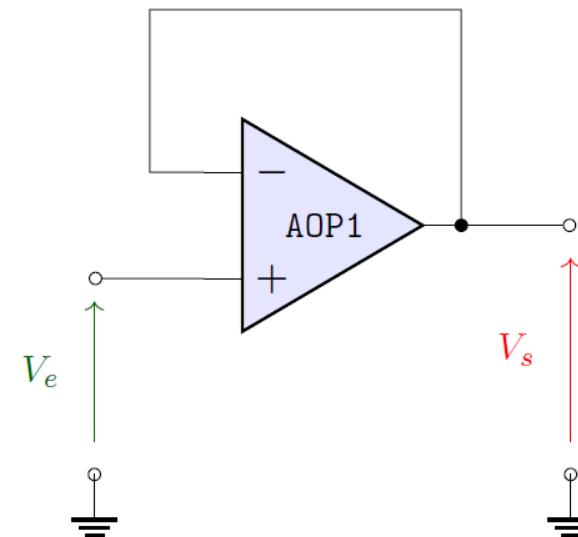
$$V_s = A \cdot (V_+ - V_-)$$

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

Saturation à $V_s = V_{cc+}$

Fonctionnement linéaire

Si contre-réaction négative (via un dipôle)



$$V_s = A \cdot (V_e - V_s) \quad \blacktriangleright$$

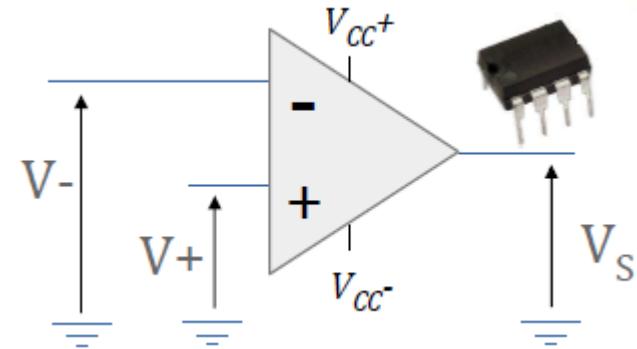
$$\frac{V_s}{V_e} = \frac{A}{A + 1}$$

Amplificateur Linéaire Intégré

Fonction de transfert / Caractéristiques

ALI / AOP

Composant actif, **amplificateur différentiel** à grand gain



FONCTION DE TRANSFERT

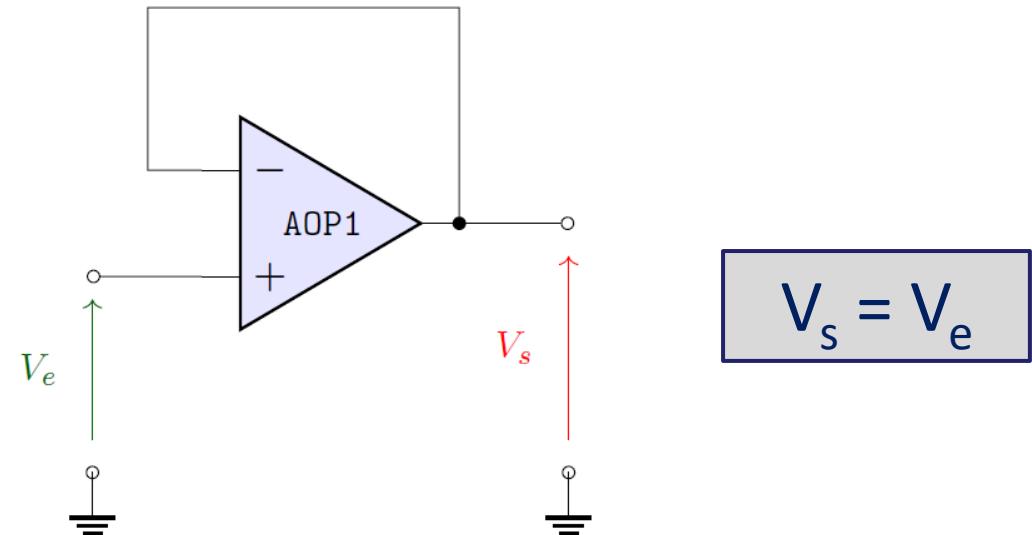
$$V_s = A \cdot (V_+ - V_-)$$

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

Saturation à $V_s = V_{cc+}$

Fonctionnement linéaire

Si contre-réaction négative (via un dipôle)



$$\blacktriangleright V_+ = V_-$$

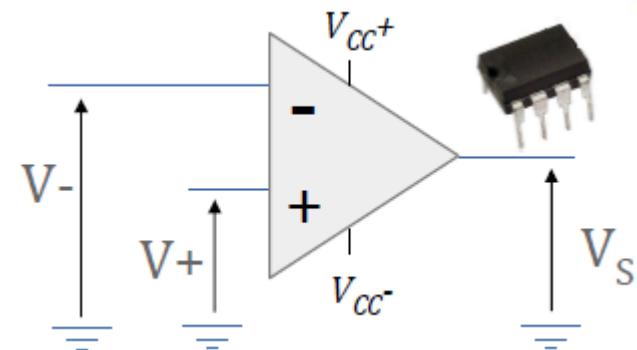
Hypothèse à vérifier...

Amplificateur Linéaire Intégré

Fonction de transfert / Bande-passante

ALI / AOP

Composant actif, **amplificateur différentiel** à grand gain



FONCTION DE TRANSFERT

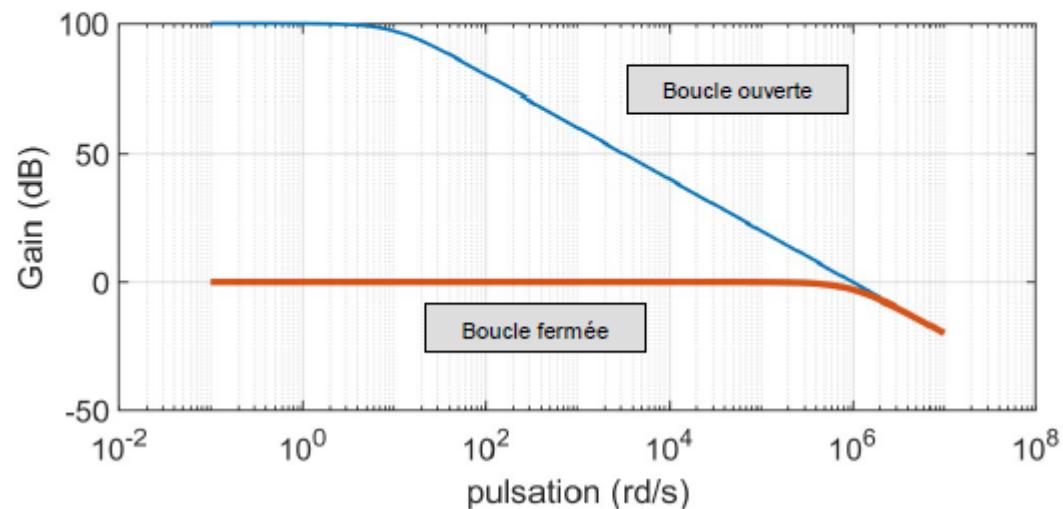
$$V_s = A \cdot (V_+ - V_-)$$

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

Saturation à $V_s = V_{cc+}$

RÉPONSE EN FRÉQUENCE

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



Propriété des montages à ALI

▶ $A \cdot BP = \text{cte}$

où A est l'amplification du montage et BP la bande passante du montage

Amplificateur Linéaire Intégré

Fonction de transfert / Boucle fermée

ALI / AOP

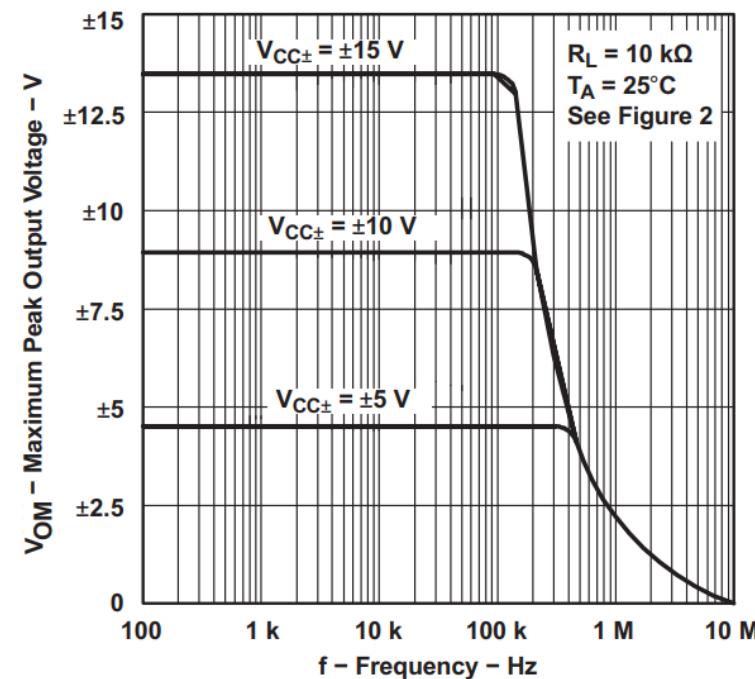
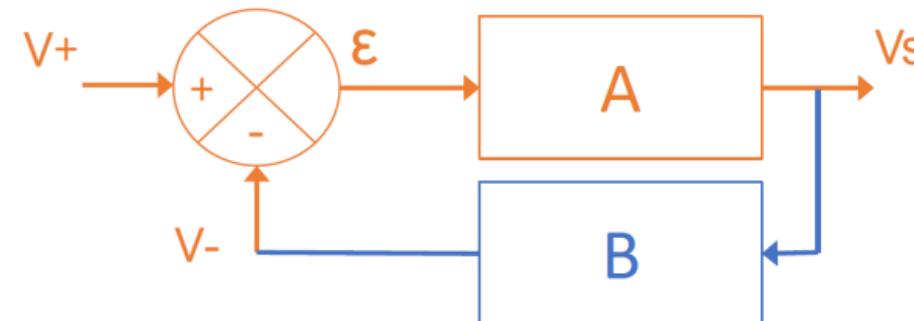


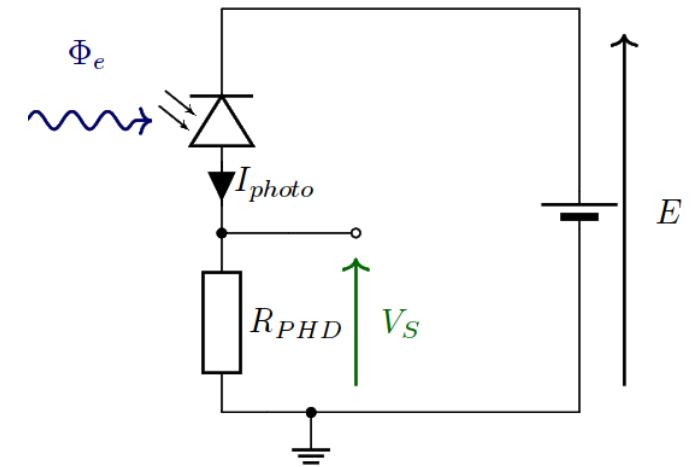
Figure 6-41. Maximum Peak Output Voltage vs Frequency

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

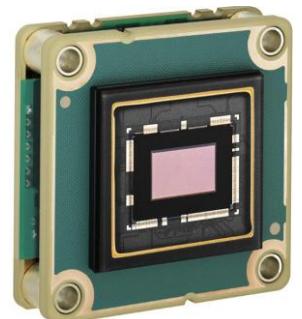


Montage de photodétection

Amélioration des performances



IDS Sensor



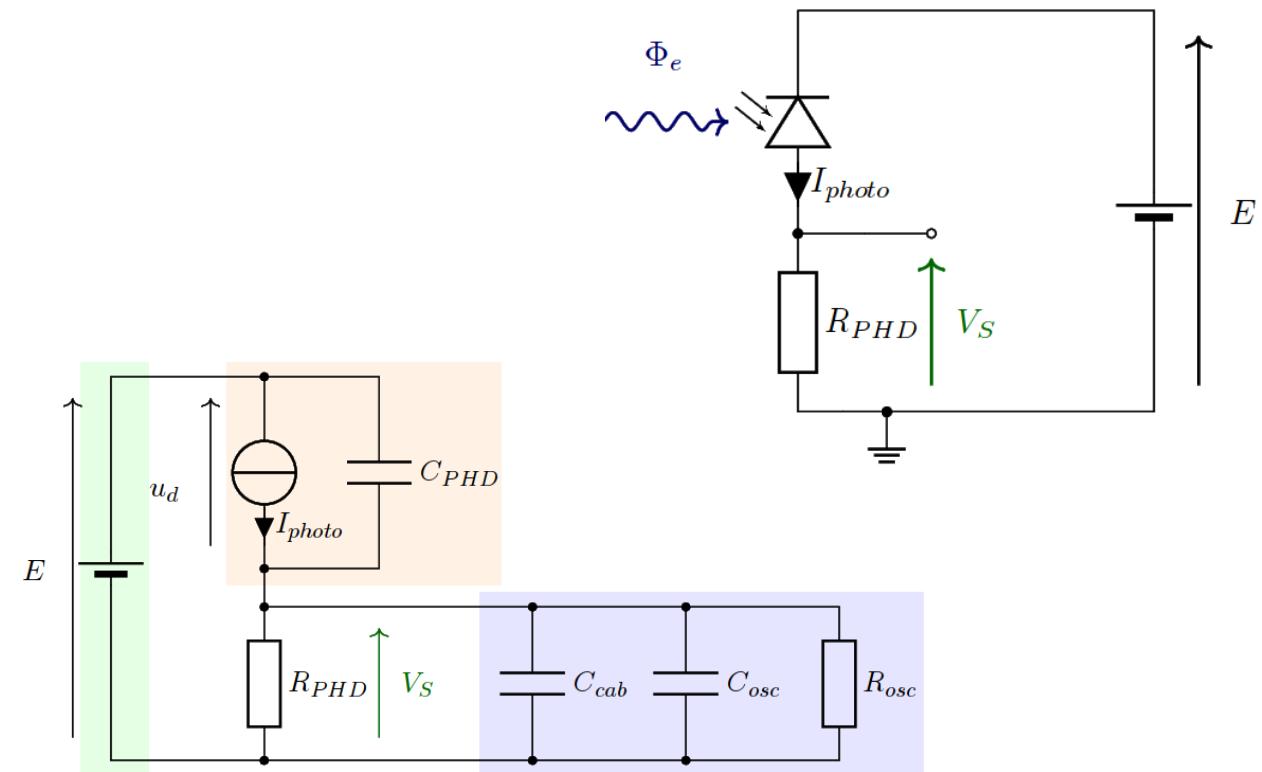
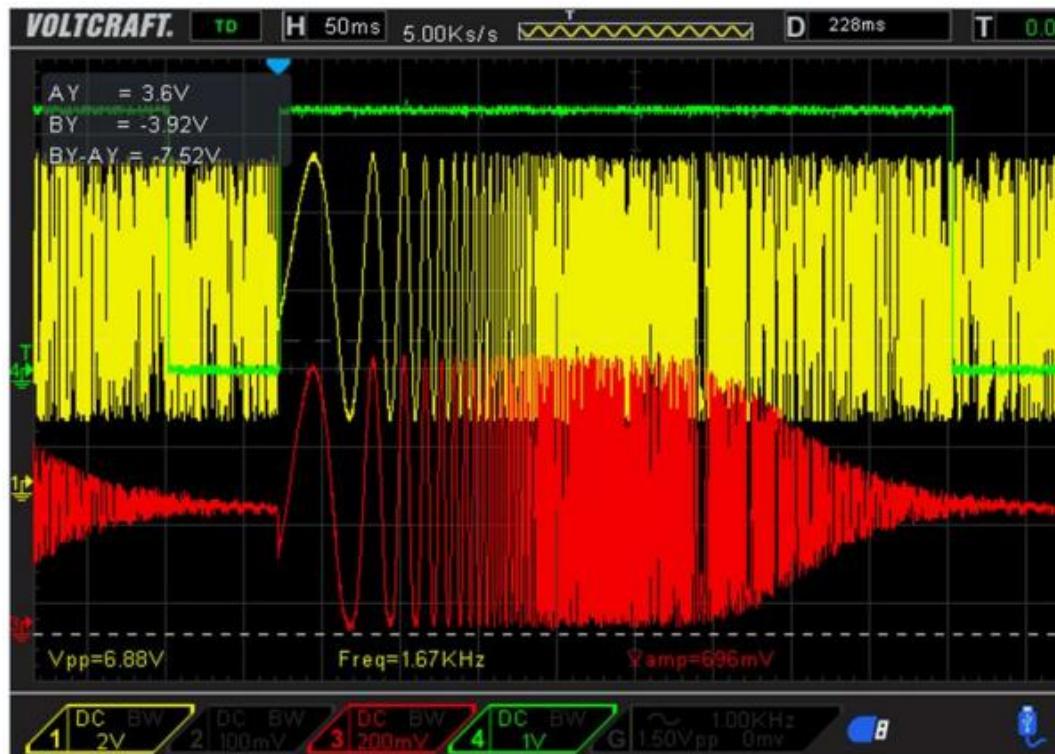
Basler Sensor / Mouser

Système de photodétection

Version « simple » / En pratique

Montage de photodétection

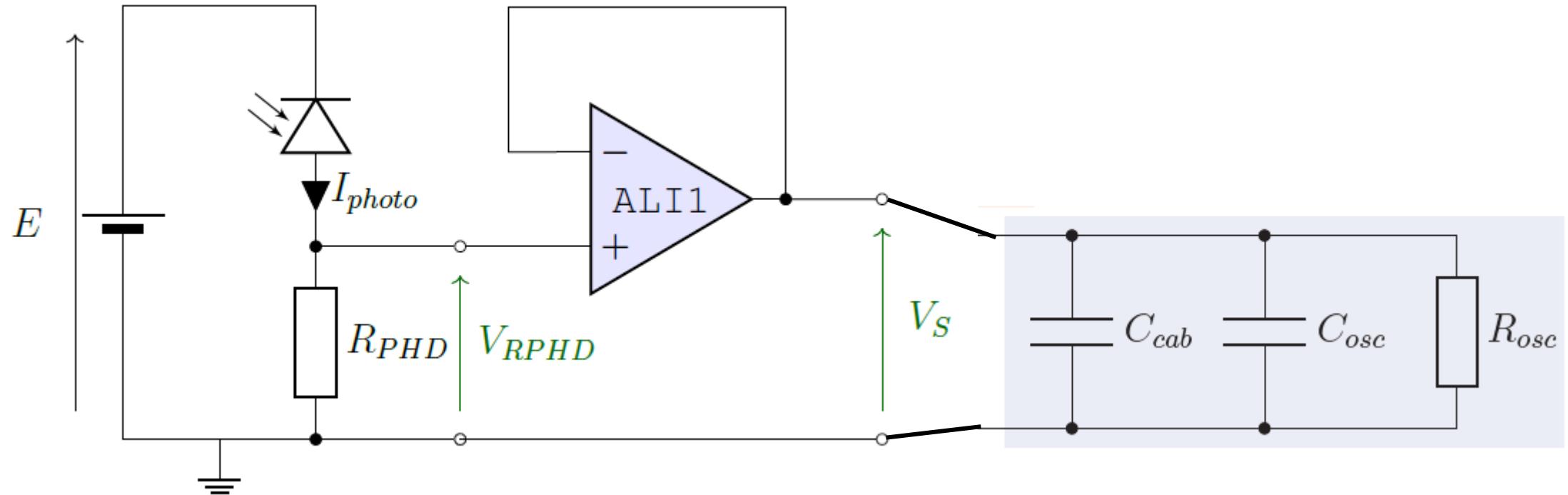
**Convertir un signal lumineux
(flux de photons) en un signal
électrique mesurable**



Système de photodétection

Version « suiveur »

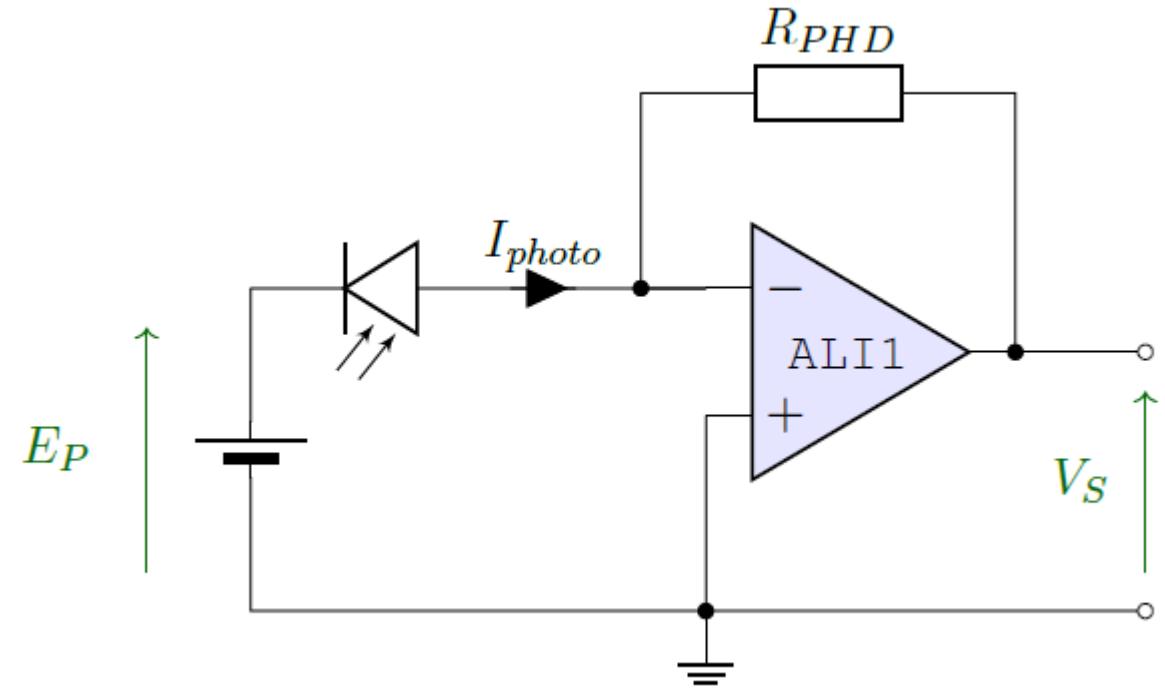
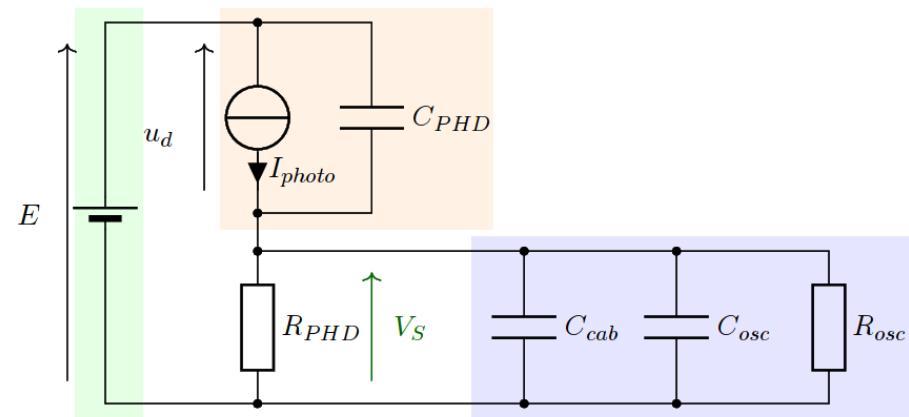
Montage de photodétection



Système de photodétection

Version « transimpédance »

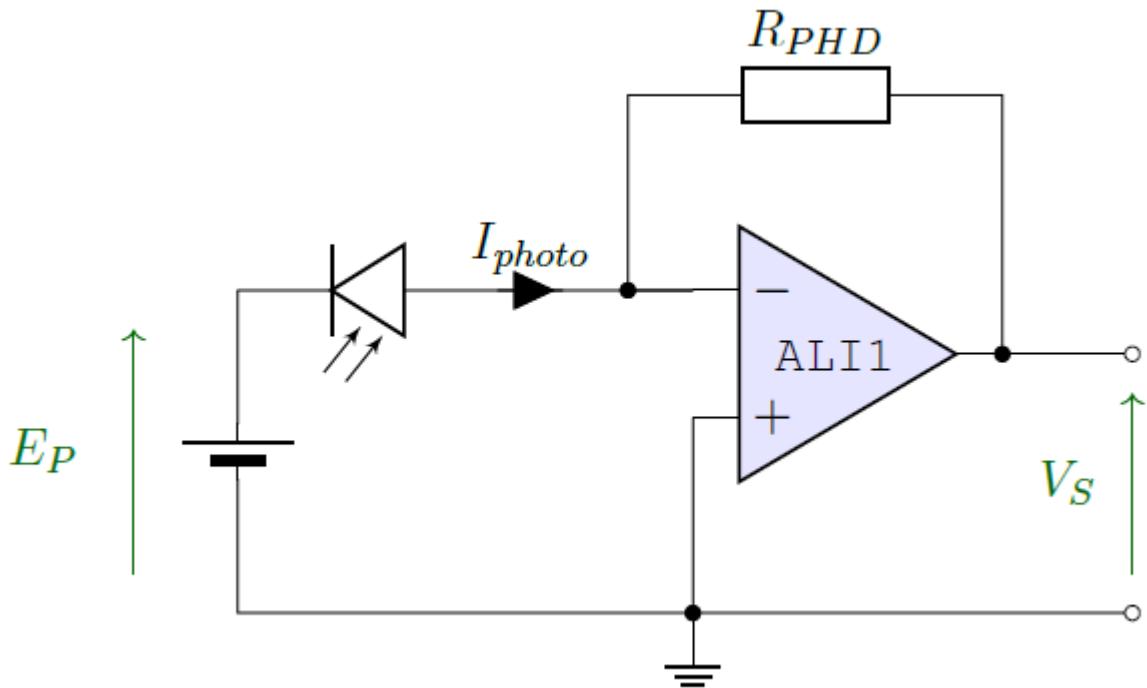
Montage de photodétection



Système de photodétection

Version « transimpédance » / En pratique

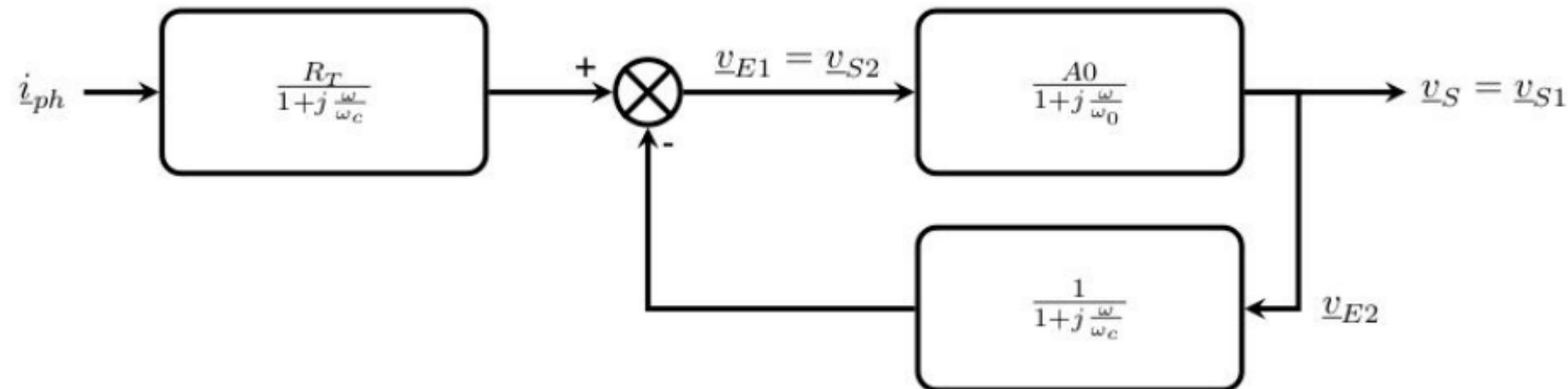
Montage de photodétection



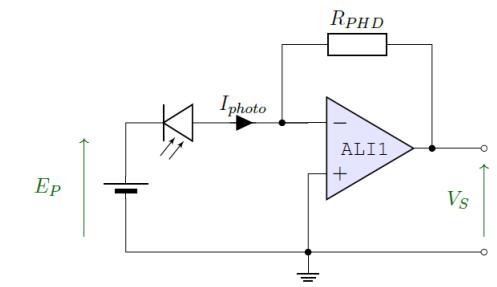
Système de photodétection

Version « transimpédance » / En pratique

Montage de photodétection

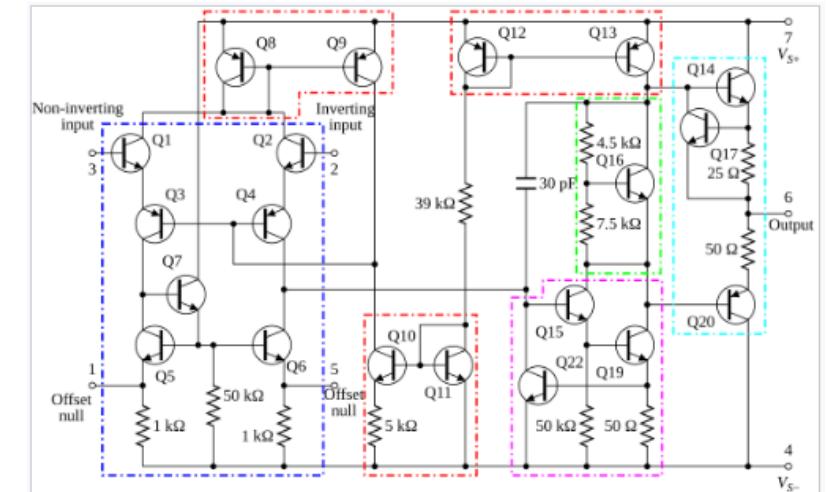


$$\frac{V_S}{I_{Phd}} = \frac{R_T \cdot A_0}{\left(1 + \frac{j \cdot \omega}{\omega_0}\right) \cdot \left(1 + \frac{j \cdot \omega}{\omega_c}\right) + A_0}$$



Transistors

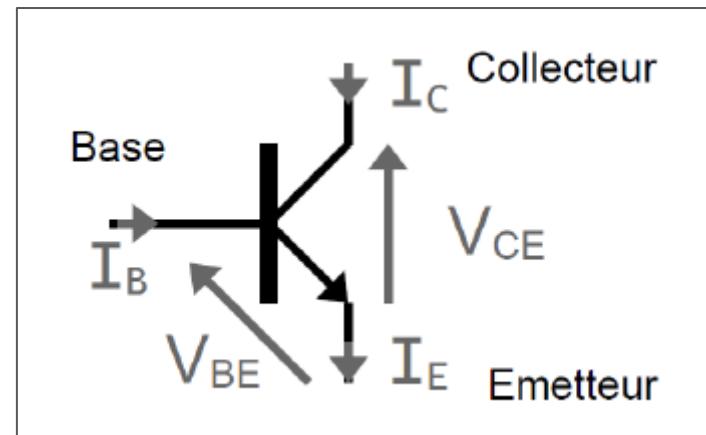
Adaptation de puissance



Adaptation de puissance / Amplification

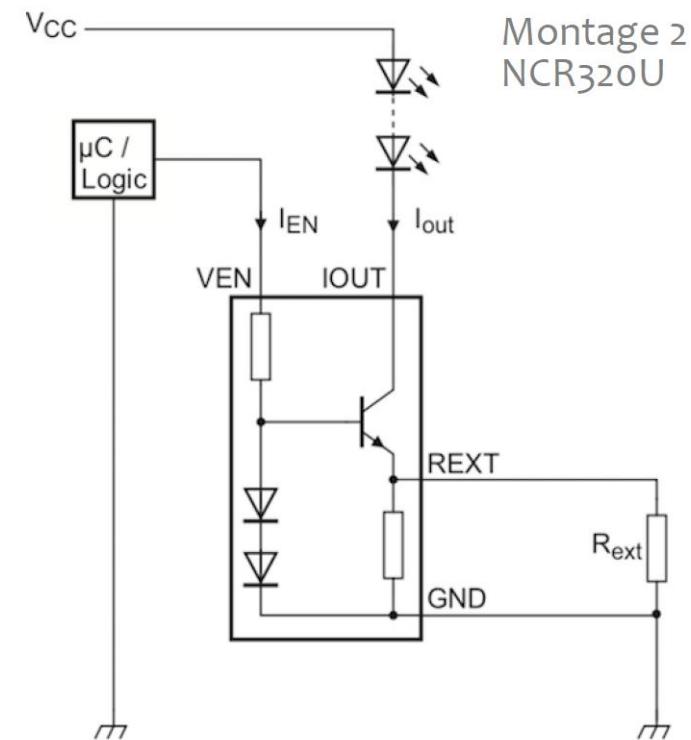
Transistor

Composant permettant de **contrôler** ou d'amplifier des tensions ou des courants



$$I_C = \beta \cdot I_B \quad \text{et} \quad I_E = I_C + I_B$$

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

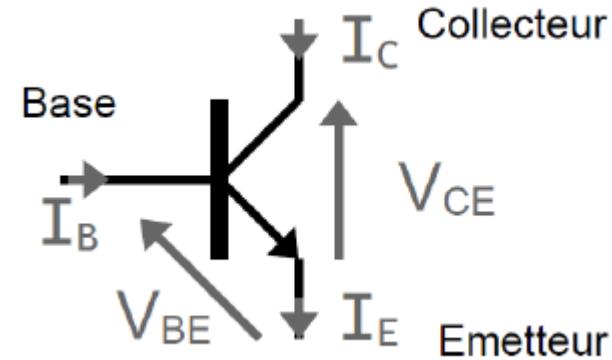


aaa-029336

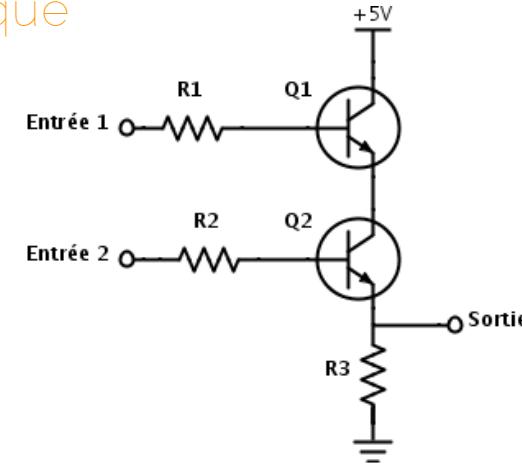
Fonctions logiques et arithmétiques

Transistor

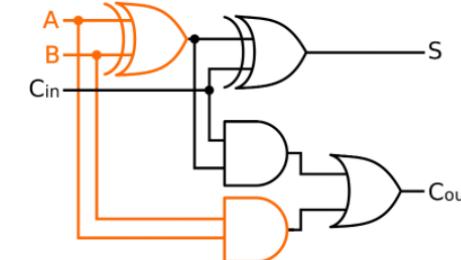
Composant permettant de **contrôler** ou d'amplifier des **tensions ou des courants**



ET logique



Additionneur

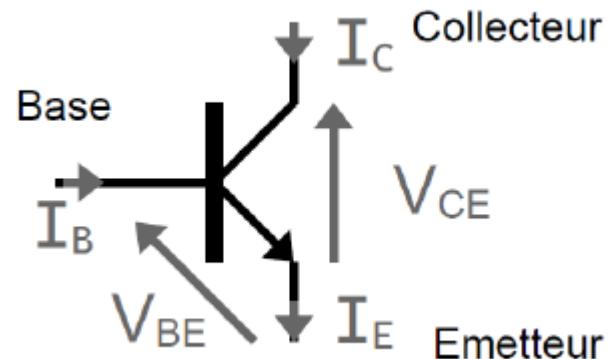


A	B	Cin	S	Cout
0	0	0	0	0
0	0	1	1	0
0	1	0	1	0
0	1	1	0	1
1	0	0	1	0
1	0	1	0	1
1	1	0	0	1
1	1	1	1	1

Fonctions logiques et arithmétiques

Transistor

Composant permettant de **contrôler** ou d'amplifier des **tensions ou des courants**



COLLECTEUR OUVERT / ÉMETTEUR OUVERT

Comparateur associé à un transistor

T :

I_B : courant entrant dans la base

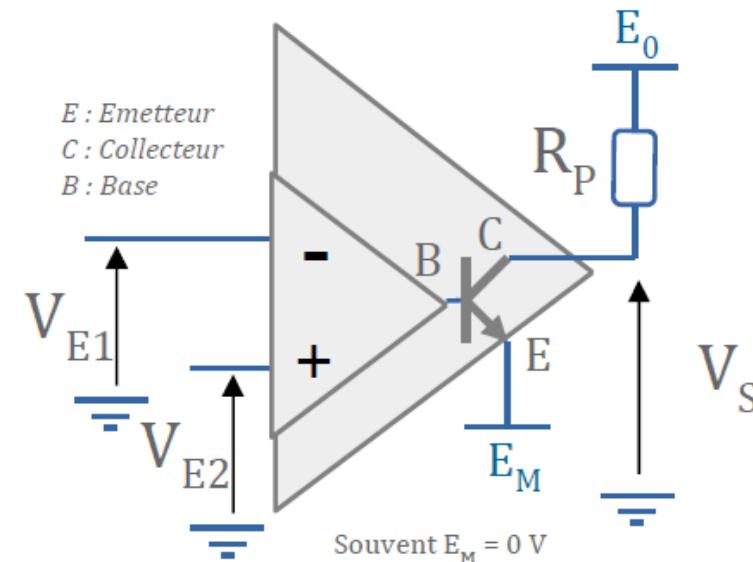
I_c : courant entrant dans le collecteur

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

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

$$\text{Si } V_{E2} > V_{E1} \rightarrow I_B > 0$$

$$V_S = E_M$$

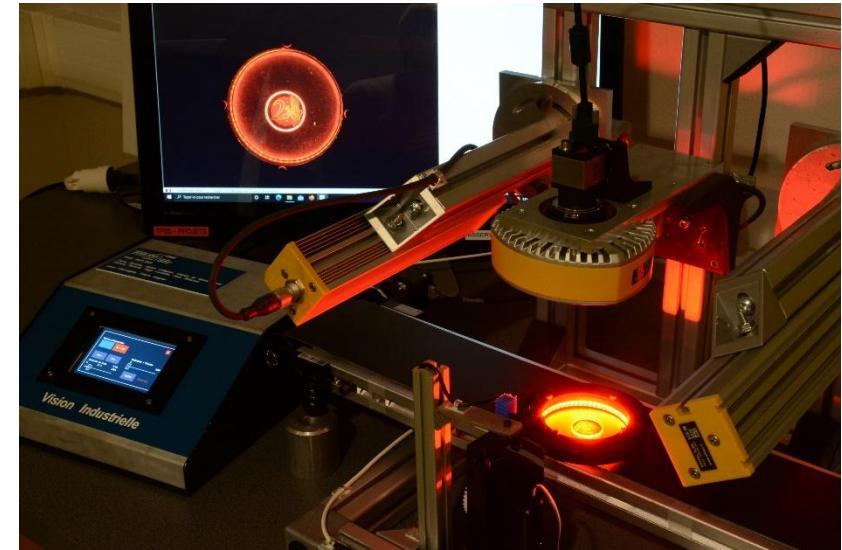


$$\text{Si } V_{E1} > V_{E2} \rightarrow I_B = 0$$

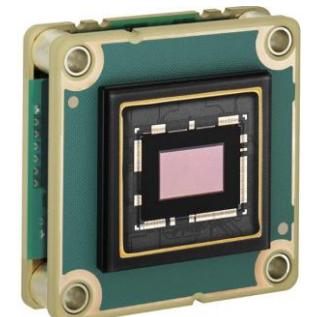
$$V_S = E_0$$

Caméras / Capteurs CMOS

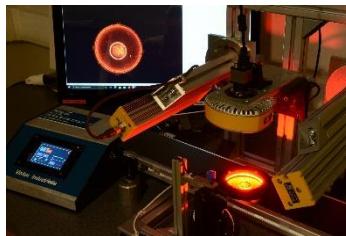
Application de la photodétection



IDS Sensor

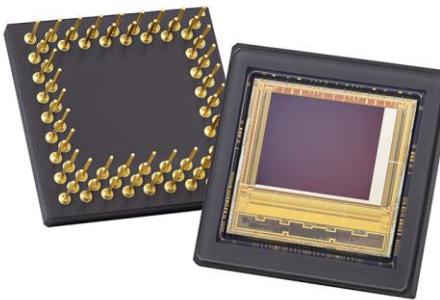
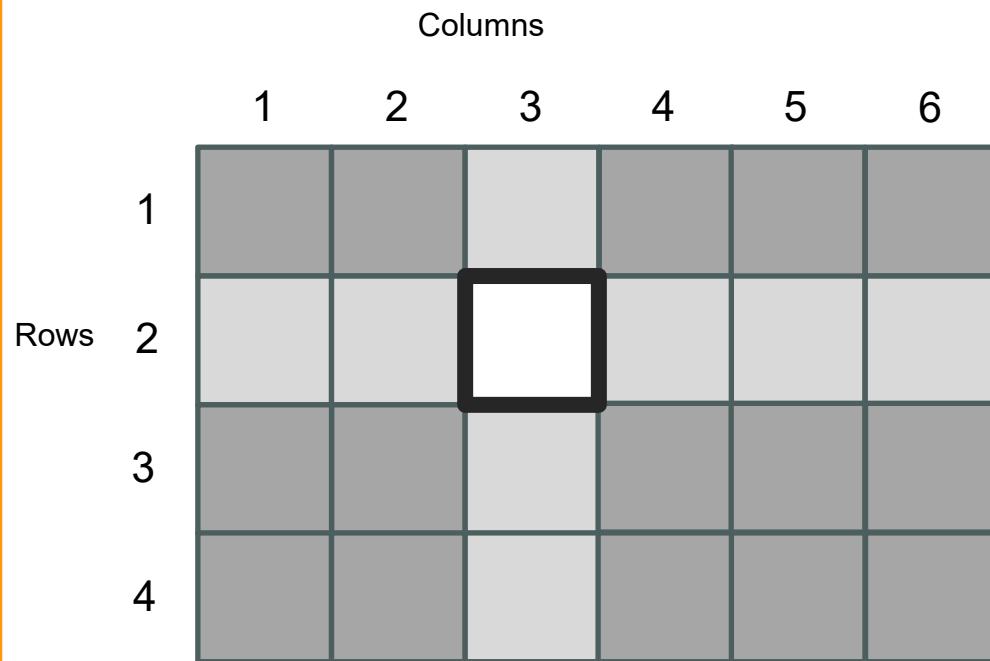


Basler Sensor / Mouser



Photodétection / Capteur CMOS

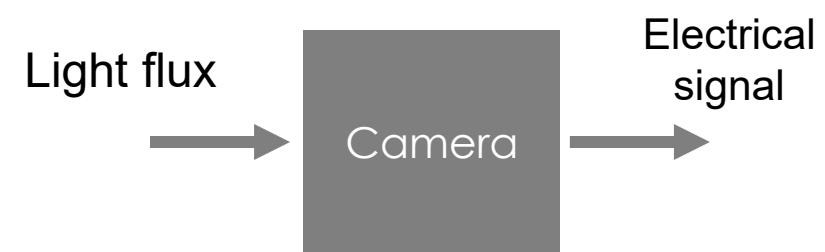
Matrice de pixels

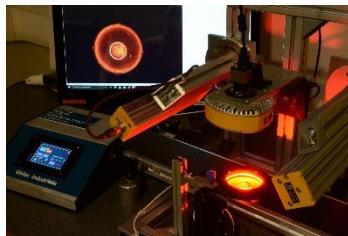


<https://imaging.teledyne-e2v.com/products/2d-cmos-image-sensors/onyxmax/>

Camera

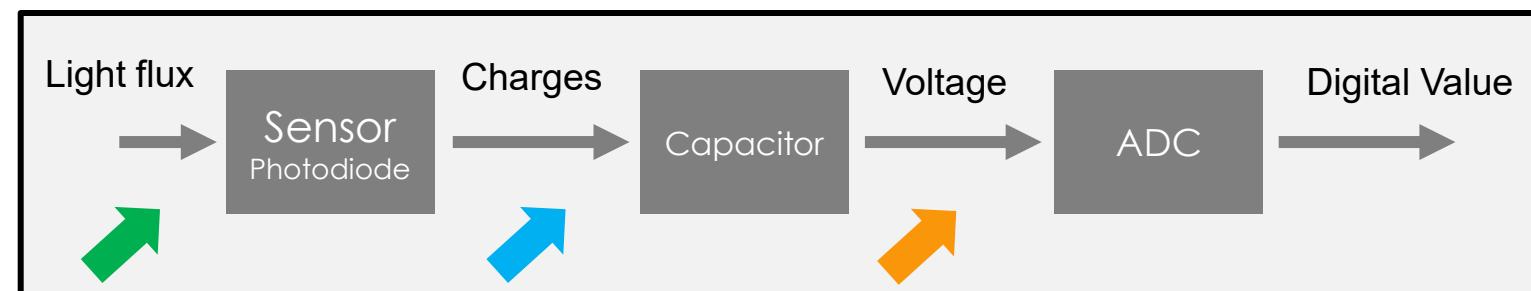
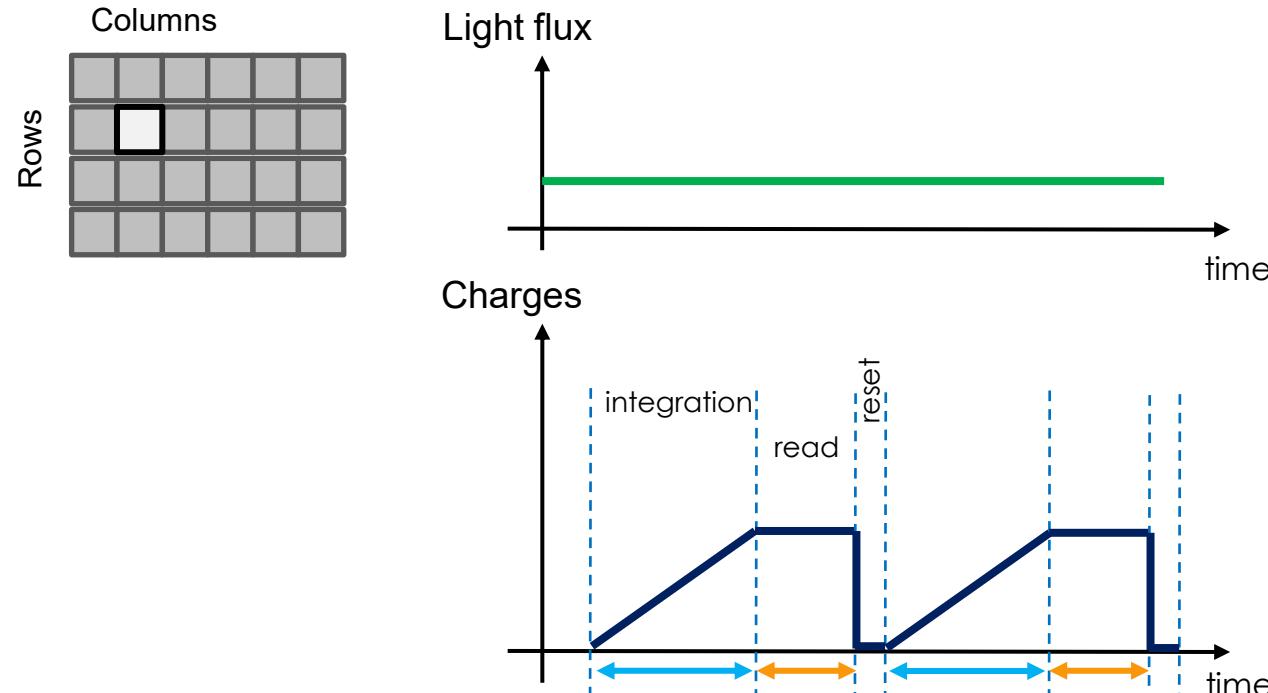
Système qui transforme un **flux de lumière** en un **signal électrique mesurable**, en fonction de la position du flux sur ce capteur



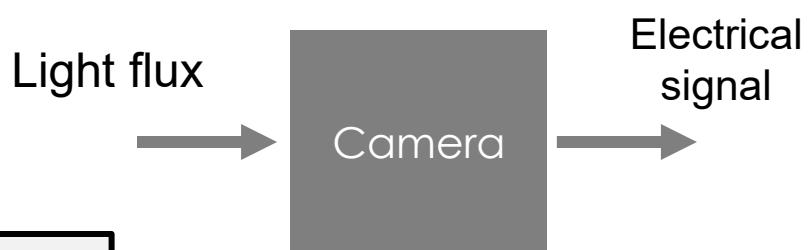


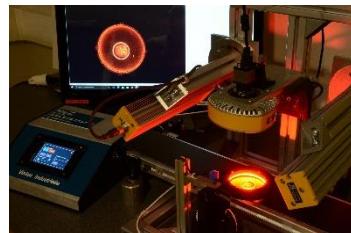
Photodétection / Capteur CMOS

Intégration de lumière



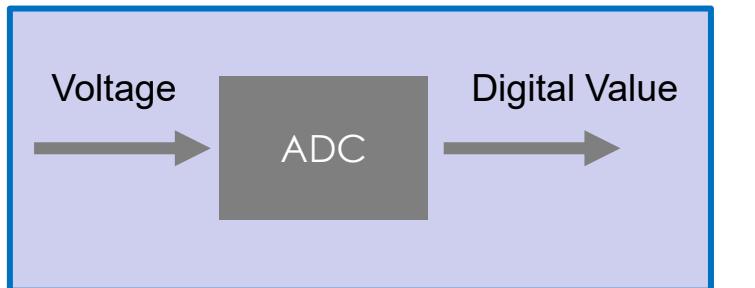
Système qui transforme un **flux de lumière** en un **signal électrique mesurable**, en fonction de la position du flux sur ce capteur





Photodétection / Capteur CMOS

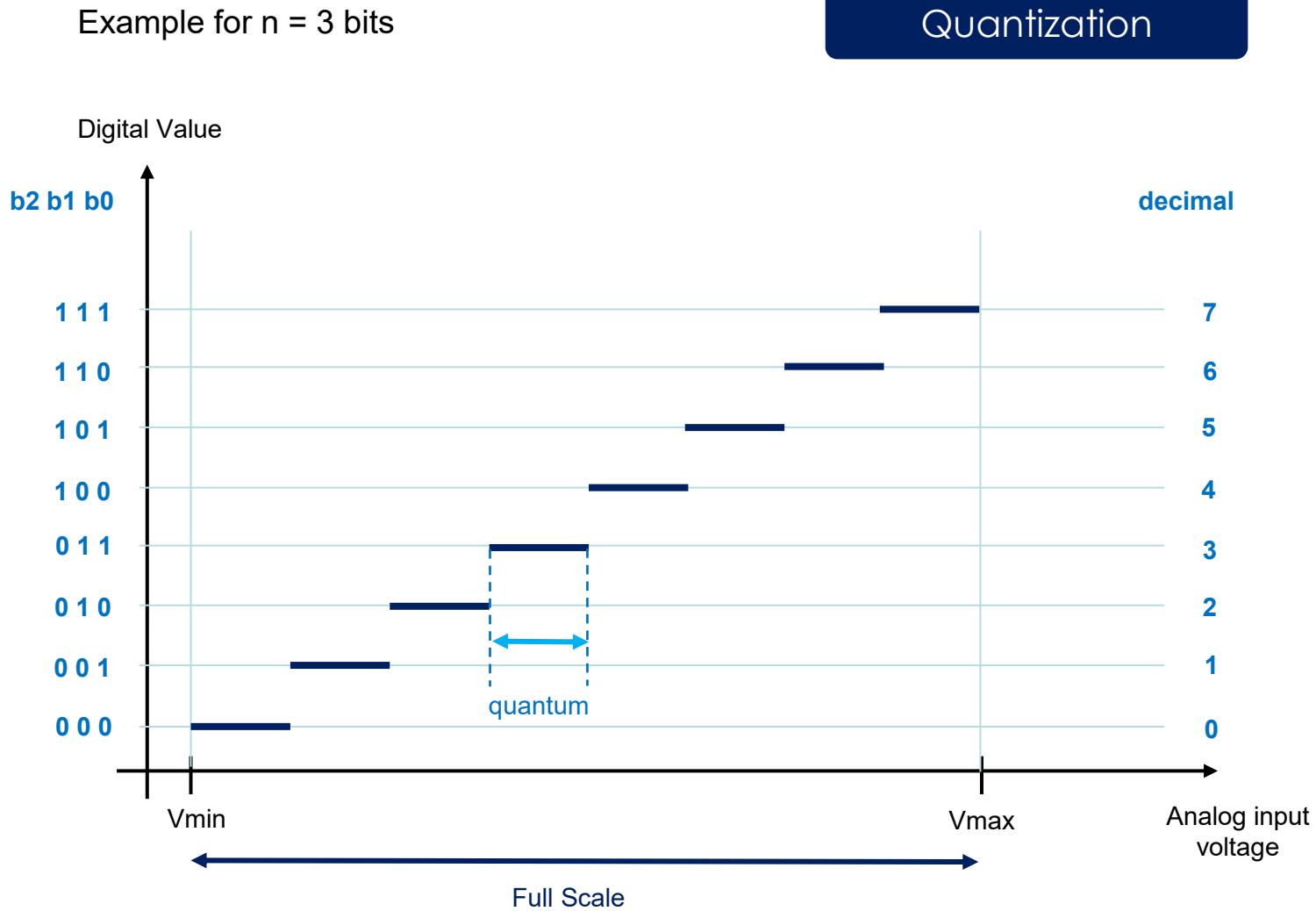
Conversion AN / Quantification

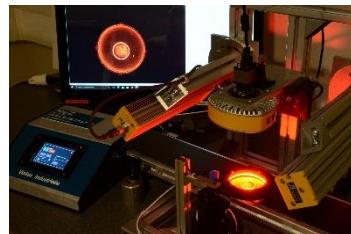


A block diagram illustrating an Analog-to-Digital Converter (ADC). On the left, an arrow labeled "Analog Input" points into a central gray rectangular block labeled "ADC". From the right side of the ADC block, four arrows point downwards to the labels b_0 , b_1 , b_2 , and b_n . A large blue brace on the far right groups these four labels under the heading "n bits".

Each bit can have one of two values: **0** or **1**

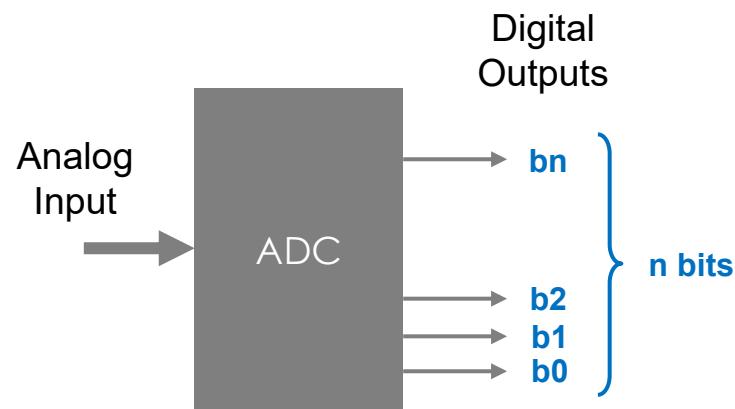
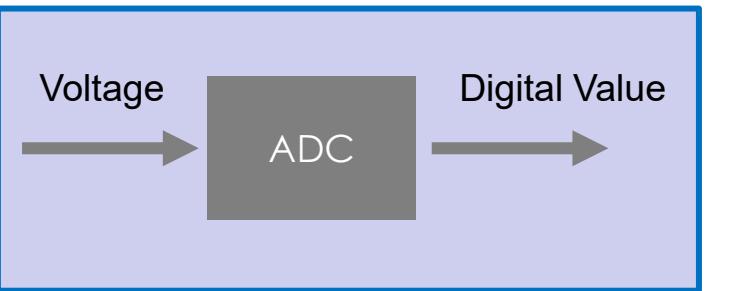
The number of different values that can be represented by **n bits** is 2^n .





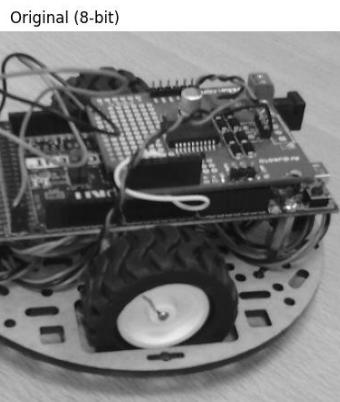
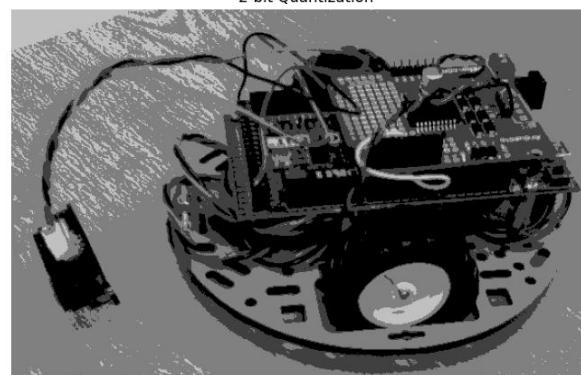
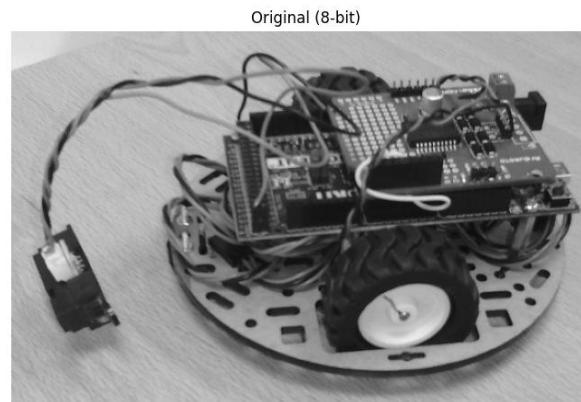
Photodétection / Capteur CMOS

Conversion AN / Quantification

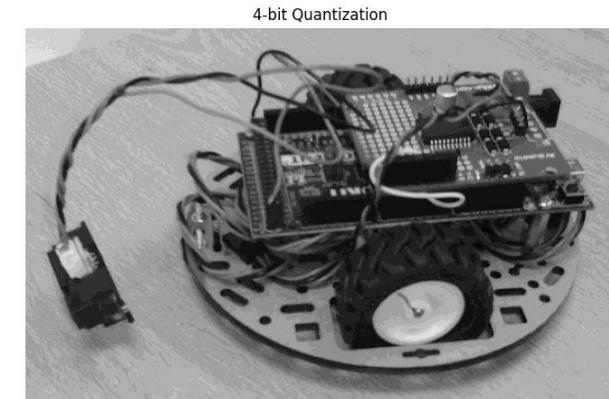


Each bit can have one of two values: **0** or **1**.

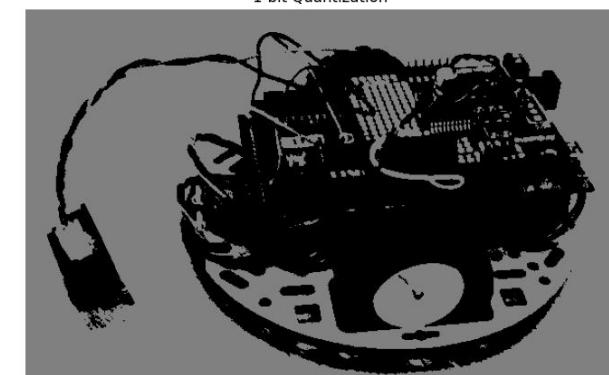
The **number of different values** that can be represented by **n bits** is 2^n .

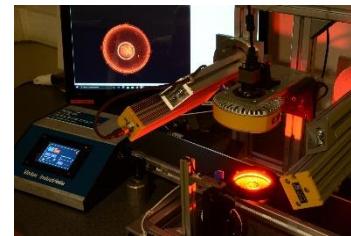


Quantization



1-bit Quantization



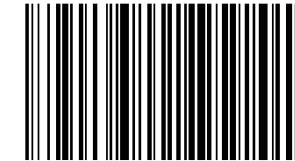


Photodétection / Capteur CMOS

Conversion AN / Echantillonnage



<https://barcode-coder.com/fr/specification-ean-13-102.html>



LEnsE 2024

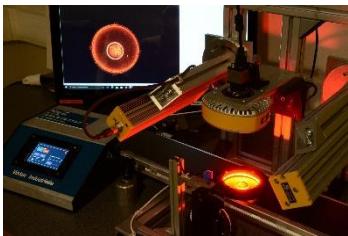
Sampling theorem

Nyquist–Shannon sampling theorem

The sampling frequency must be equal to or **greater than twice** the frequency associated with the finest detail in the image (edges).

With a grid spacing of d , a periodic component with a period higher than $2.d$ can be reconstructed.



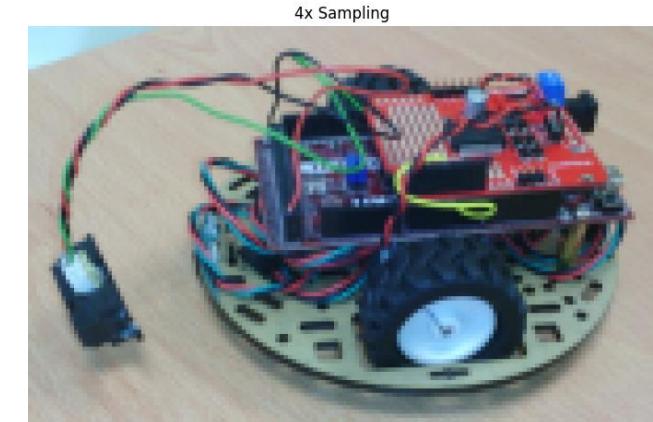
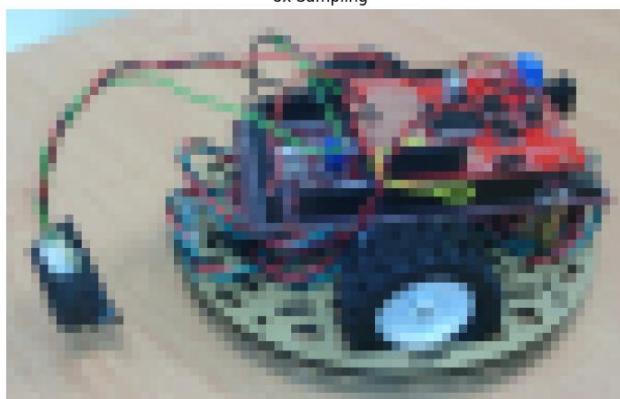
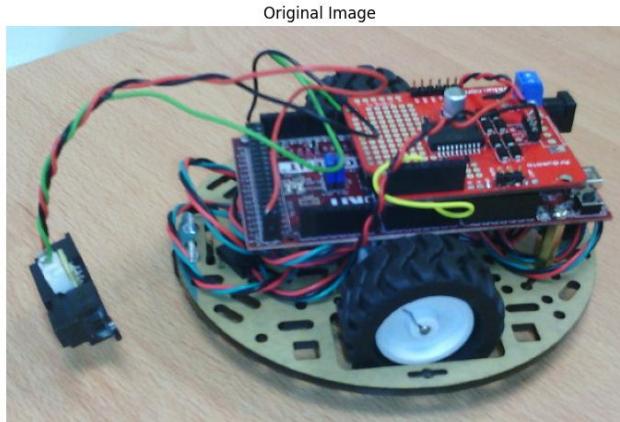


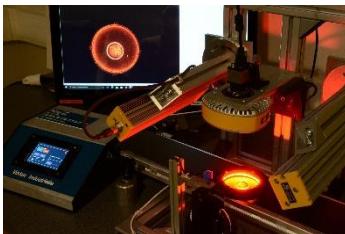
Photodétection / Capteur CMOS

Conversion AN / Echantillonnage

Voltage → ADC → Digital Value

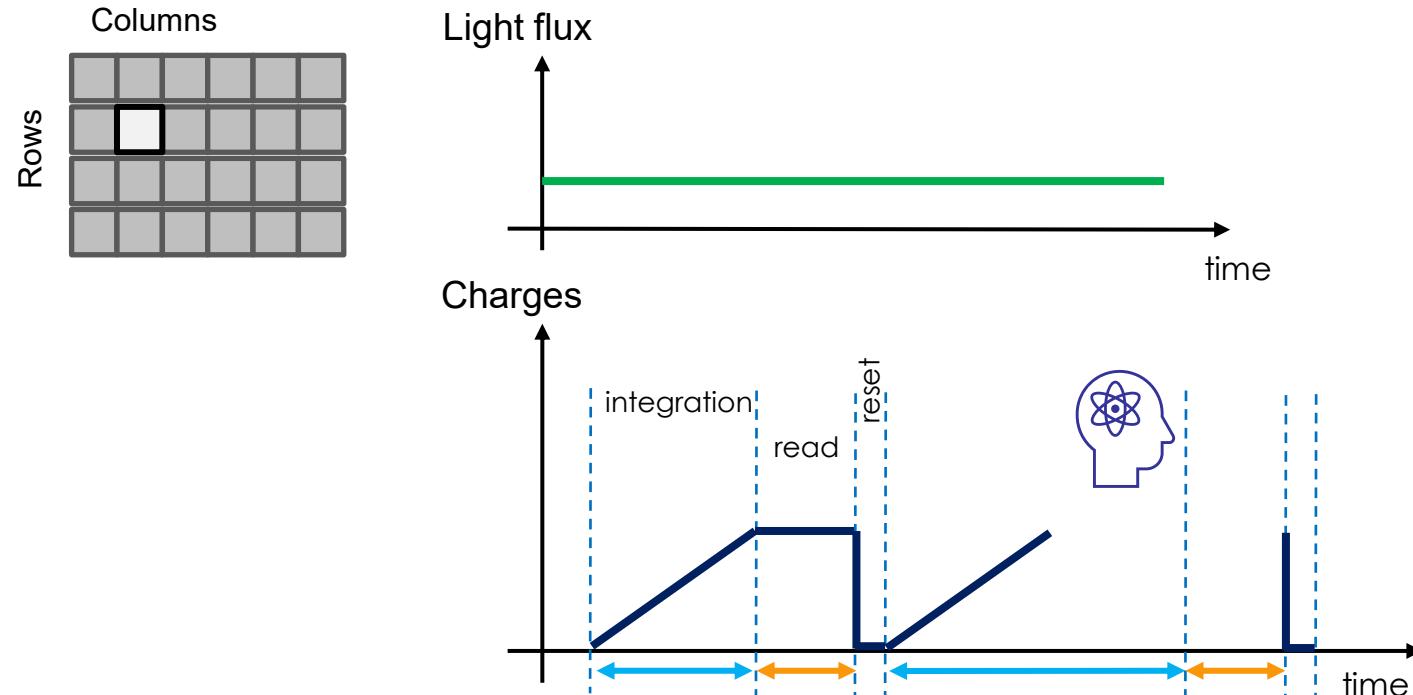
Sampling





Photodétection / Capteur CMOS

Intégration de lumière

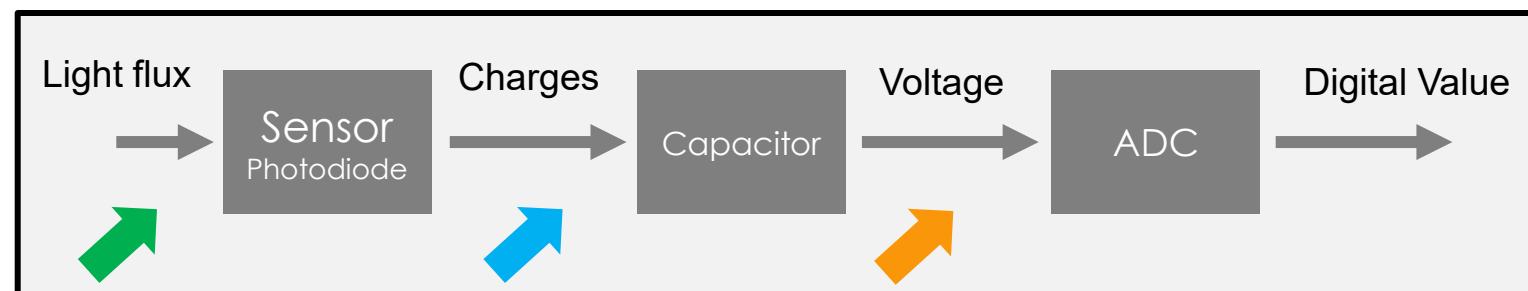


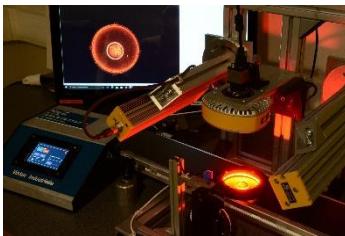
Exposure Time

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

This parameter determines the amount of light collected.

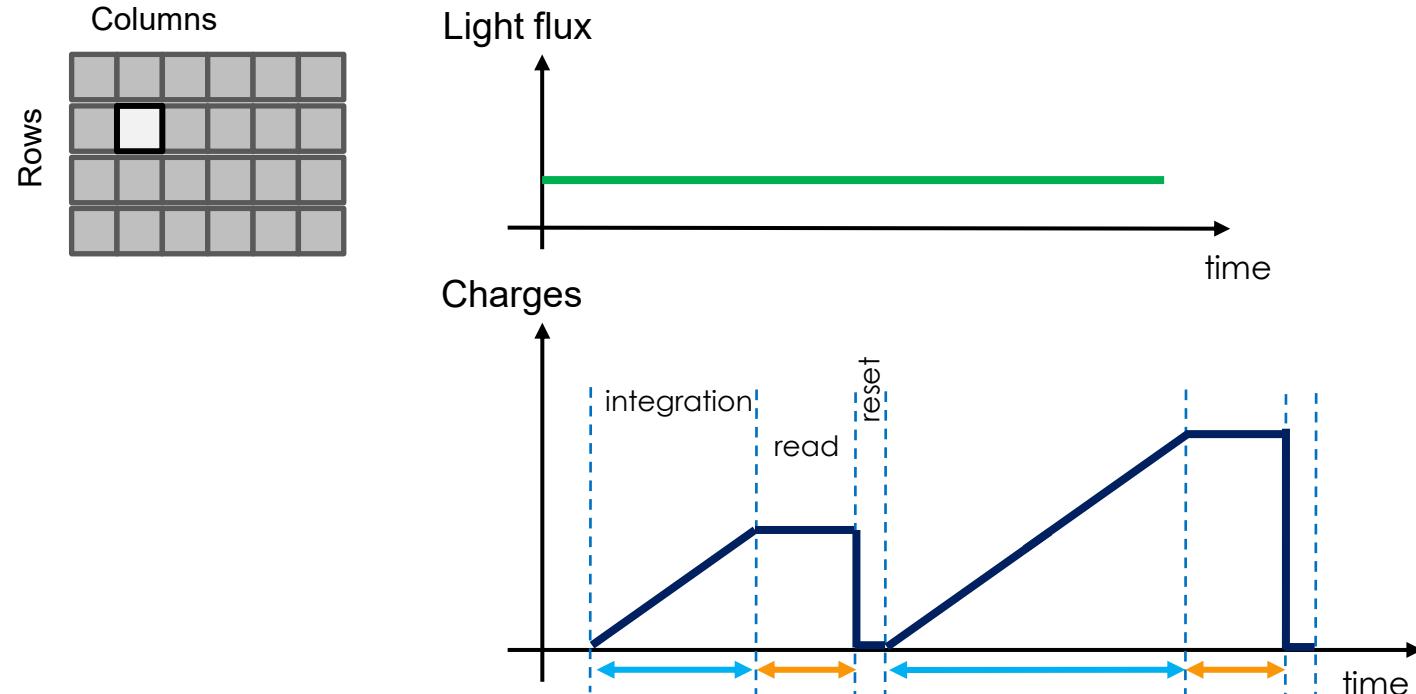
i.e. the amount of collected charges coming from the sensor stored in a capacitor





Photodétection / Capteur CMOS

Intégration de lumière

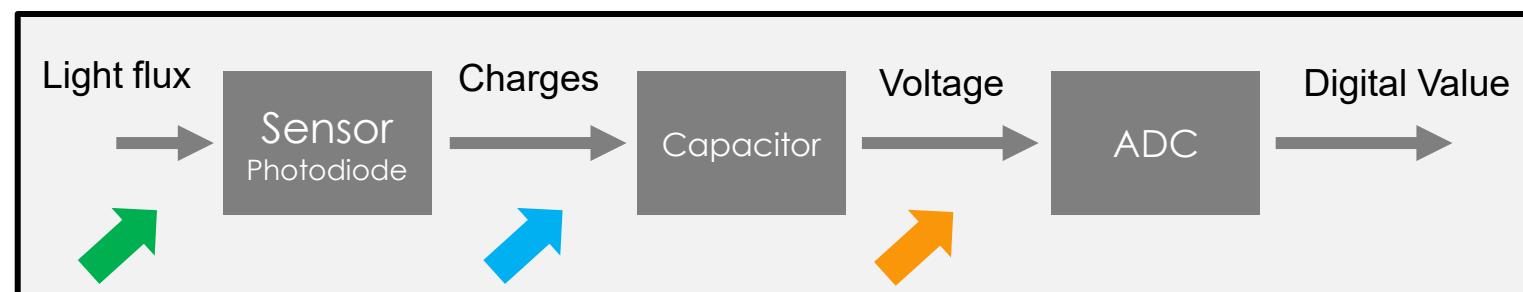


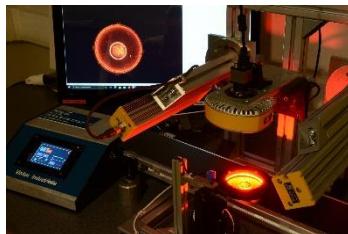
Exposure Time

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

This parameter determines the amount of light collected.

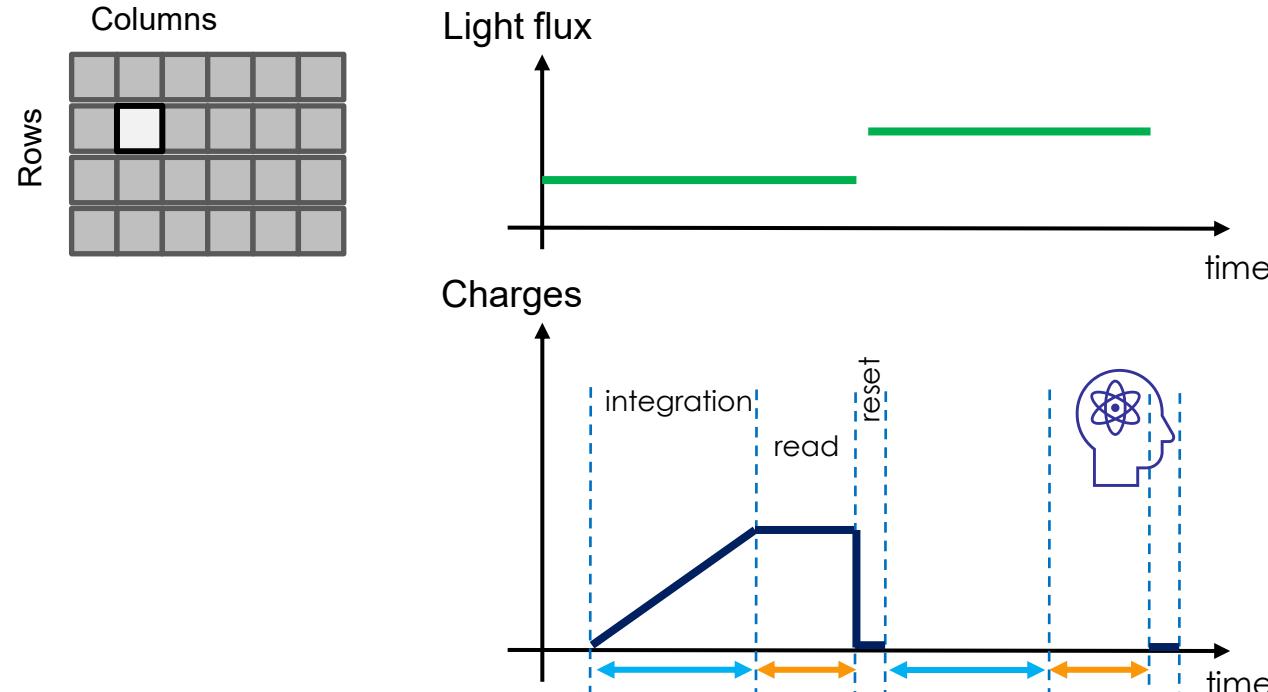
i.e. the amount of collected charges coming from the sensor stored in a capacitor





Photodétection / Capteur CMOS

Intégration de lumière

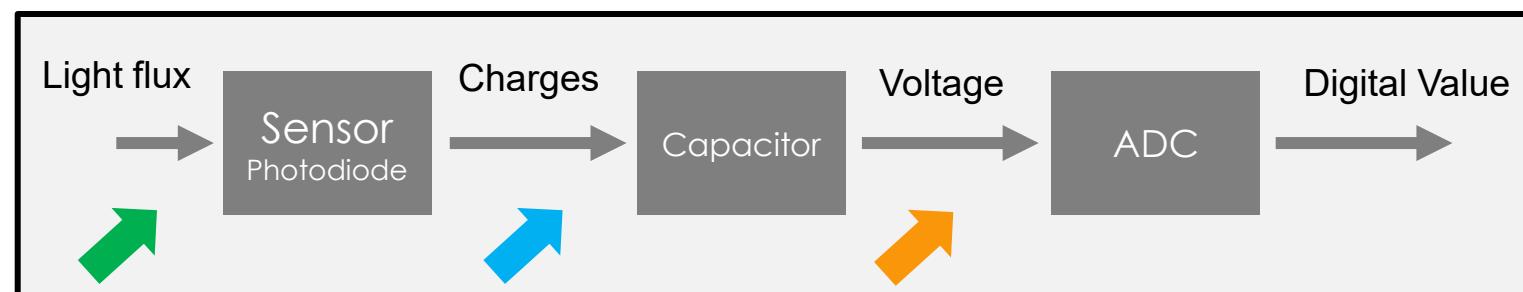


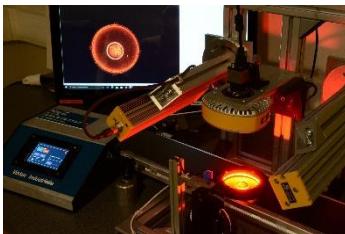
Exposure Time

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

This parameter determines the amount of light collected.

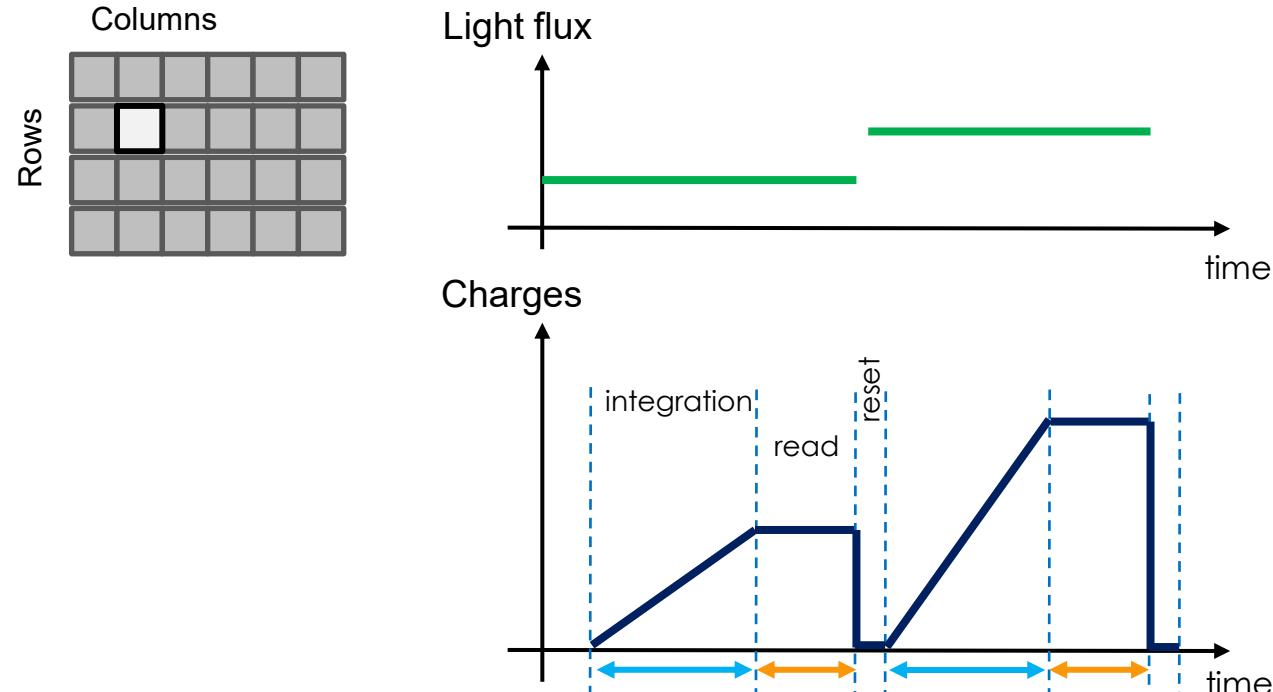
i.e. the amount of collected charges coming from the sensor stored in a capacitor





Photodétection / Capteur CMOS

Intégration de lumière

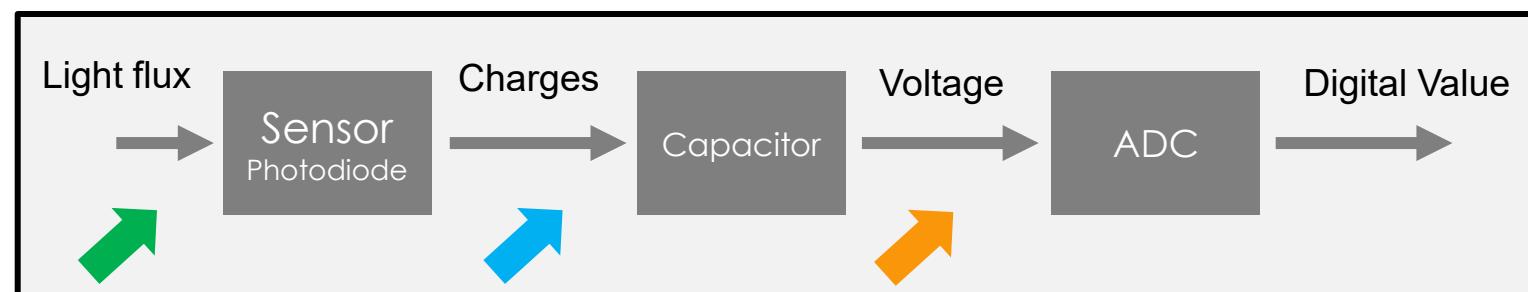


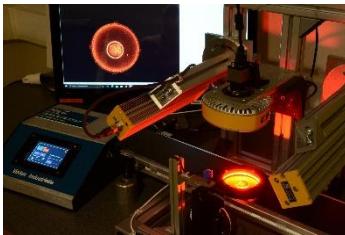
Exposure Time

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

This parameter determines the amount of light collected.

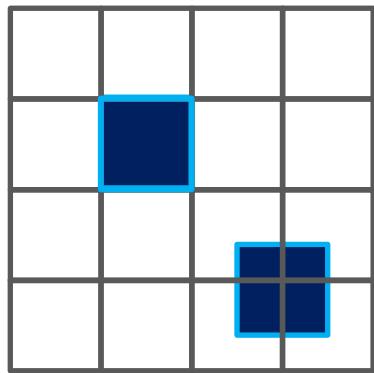
i.e. the amount of collected charges coming from the sensor stored in a capacitor





Photodétection / Capteur CMOS

Résolution spatiale

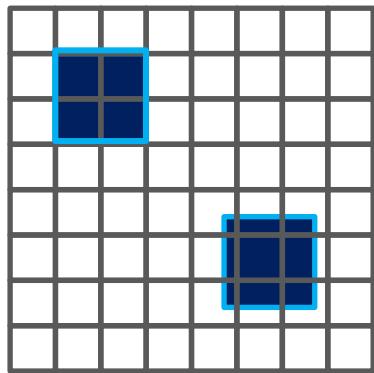


Small object to detect

$$P = d$$

Spatial resolution / P

Distance observed by a single pixel in a given direction



Security factor S

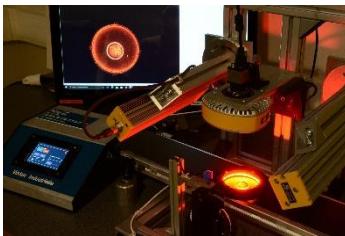
$$P = \frac{d}{S}$$

This security factor is due to the Nyquist-Shanon theorem.

And $S \geq 2$

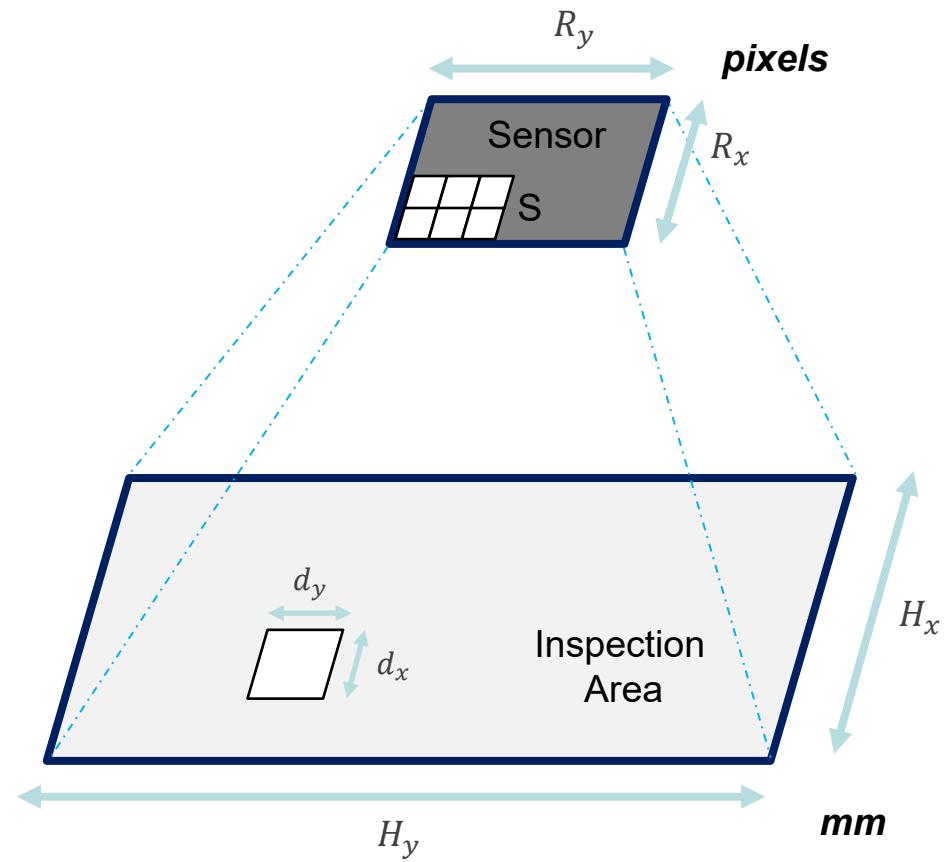


*To verify if the spatial resolution is good enough, **calibration target** can be used. (Foucault)*



Photodétection / Capteur CMOS

Résolution spatiale



Spatial resolution / P

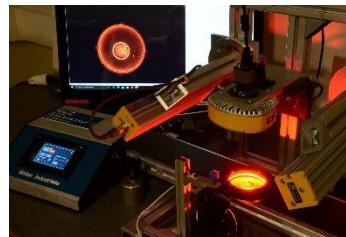
Distance observed by a single pixel in a given direction

$$P = \frac{d}{S}$$

Sensor resolution (pixels)

$$R = \frac{H}{P} = \frac{S \times H}{d}$$

H (mm) →	R (px)
d (mm) →	S (px)
P (mm) →	1 (px)



Photodétection / Capteur CMOS

Intérêt de l'objectif devant un capteur

Schémas empruntés au cours d'optique instrumentale (SC19)
de Sébastien de ROSSI

