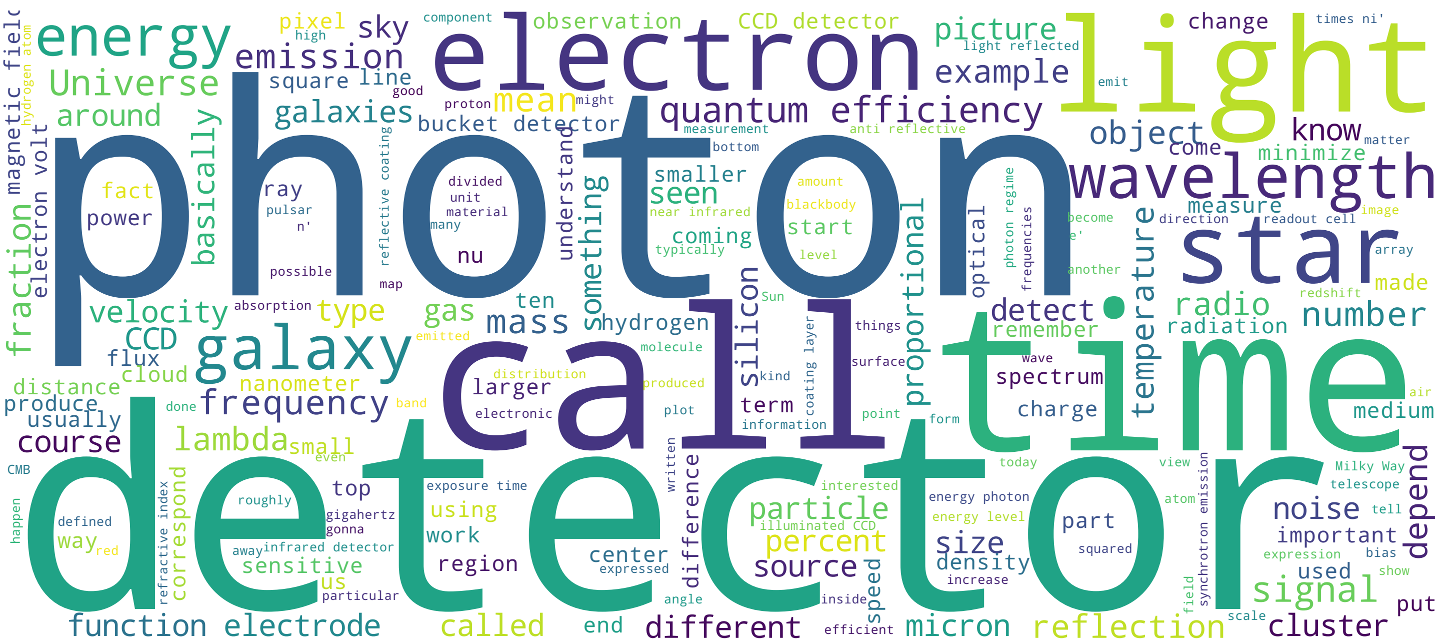
High energy photon detection

The Universe At Radio Wavelengths

Jean-Paul Knieb



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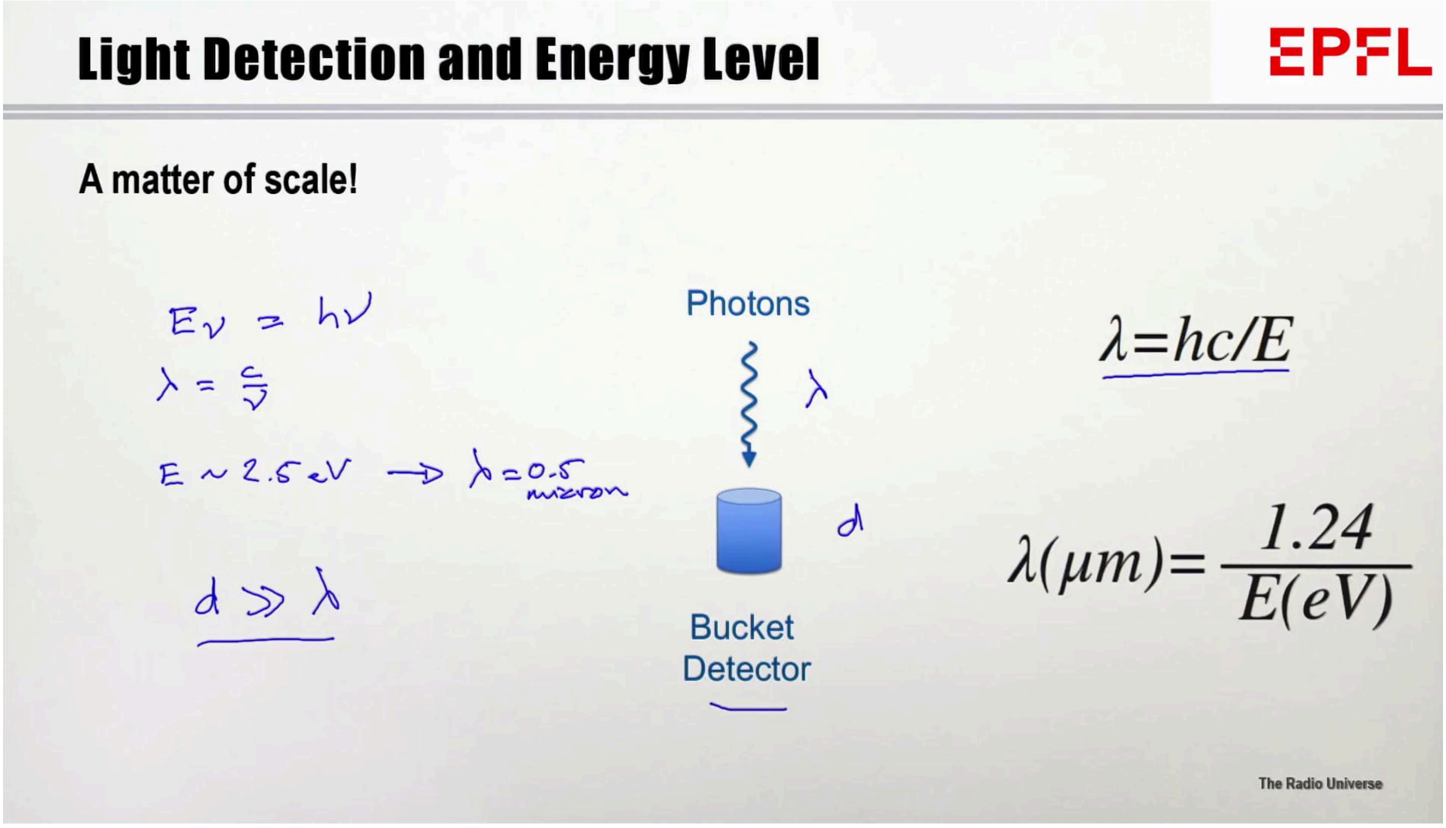
Video

We've seen that the detection of light depends on the energy of the photons we want to detect. For high energy photon, detection is based on the particle concept of light and for low energy photon, detection is based on the wave concept of light. We will explore today some of the detector concepts used for light detection in the visible, X-ray and infrared. We will start with visible light and then we will expand to other bands.

Notes

Summary

0m 05s

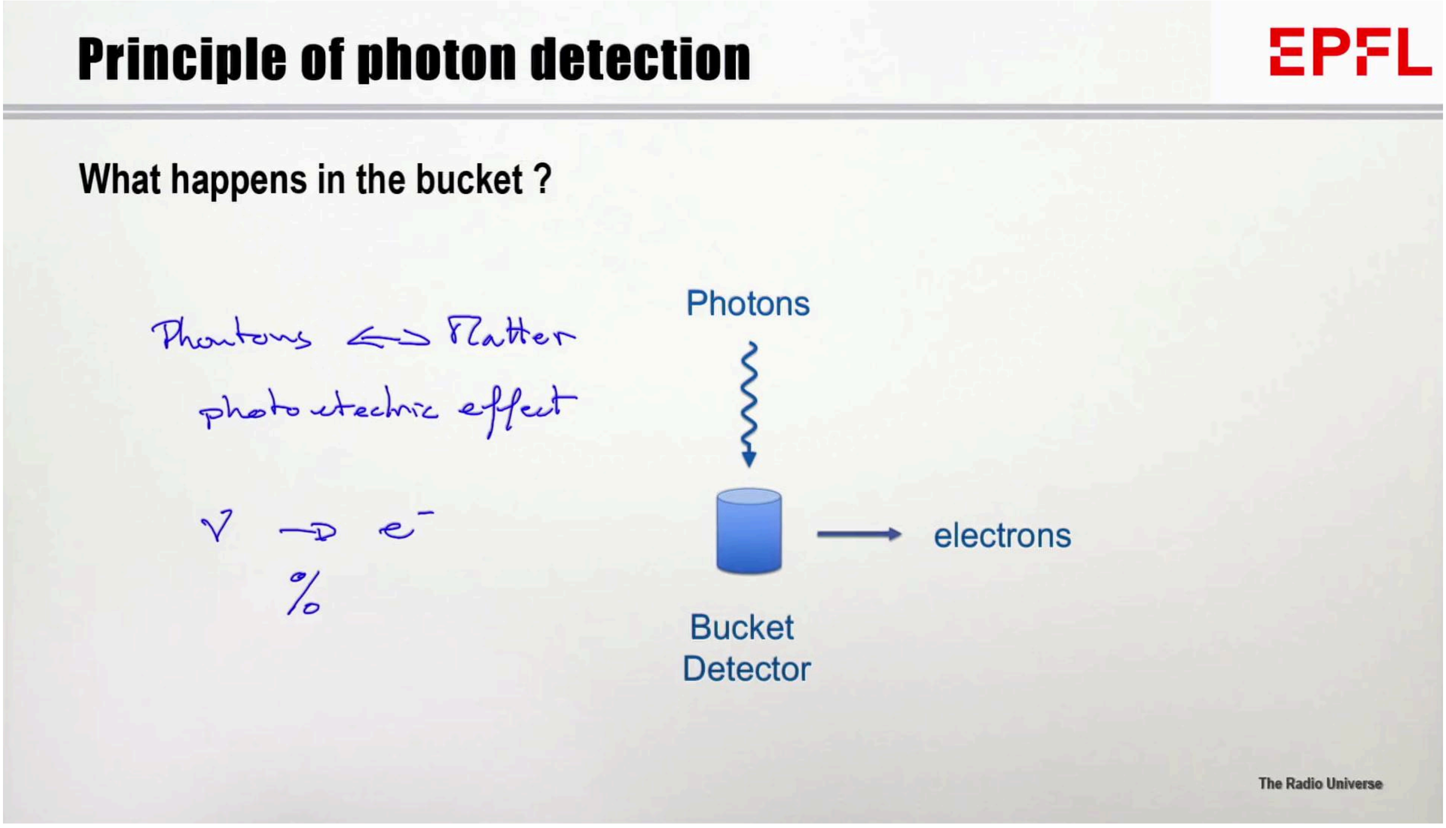


To start with we have to understand that light detection will depend on the energy level of our photons. Indeed, its matter of scale. The energy of the photon can be written 'h nu' where nu is the frequency, 'h' is the Planck constant and we can turn that into some size which is the wavelength which is lambda equal 'c' over nu. So that means we can write lambda as 'hc' over the energy. So if we are using typical scale like microns for lambda and electron volts for the energy, the relation is lambda is equal 1.24 over 'E'. So if you have an energy which is about 2.5 electron volt then the lambda the wavelength is equal to 0.5 micron. This is the wavelength of the visible domain which correspond to the light we're sensitive with our eye. So when we want to detect some photons with wavelength lambda usually what you want to do if you consider photons as particles is to put a bucket in front of your light and then you're gonna try to count the photons coming into your bucket detector. Of course, your bucket detector has a given size 'd' and if you want this to be efficient then you need to have the dimension of your bucket detector larger than the wavelength. So as I was saying, detecting photons will depend on some scale.

Notes

Summary

0m 38s

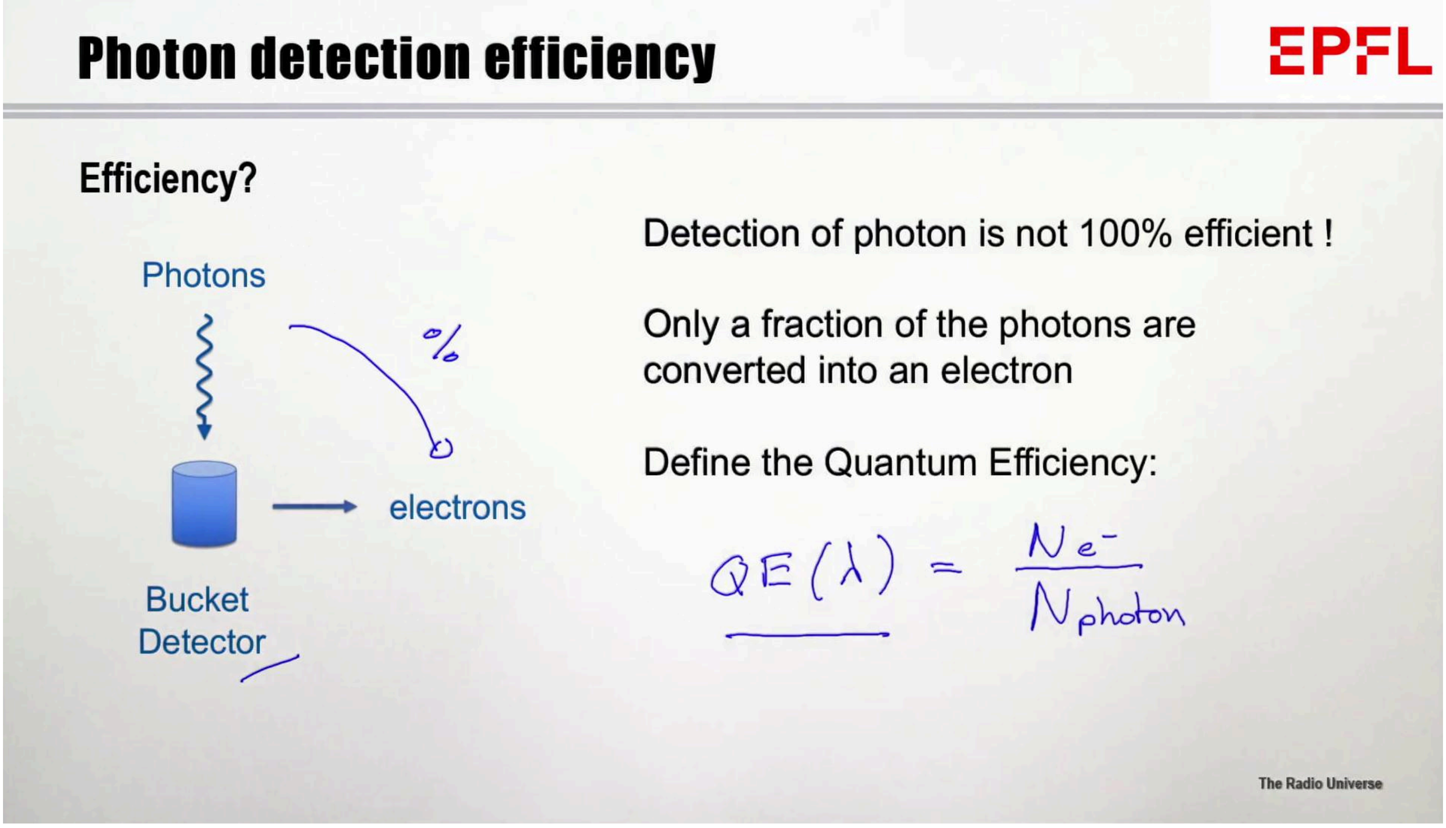


So if we have this picture of a photon that we want to detect in the bucket detector, what might happen there? You know, or we're gonna count the photons. Well, the idea here is that photons can interact with matter. We've seen that. That's what we call the photoelectric effect where we're gonna turn photons into electrons. Of course, this transformation from photons to electrons is not something which is perfect. So only a fraction of the photons are gonna be turned into electrons. But that's something we can quantify and we can calibrate. So then when we have electrons in our detector then we can use some electronics to basically count the charges.

Notes

Summary

2m 36s

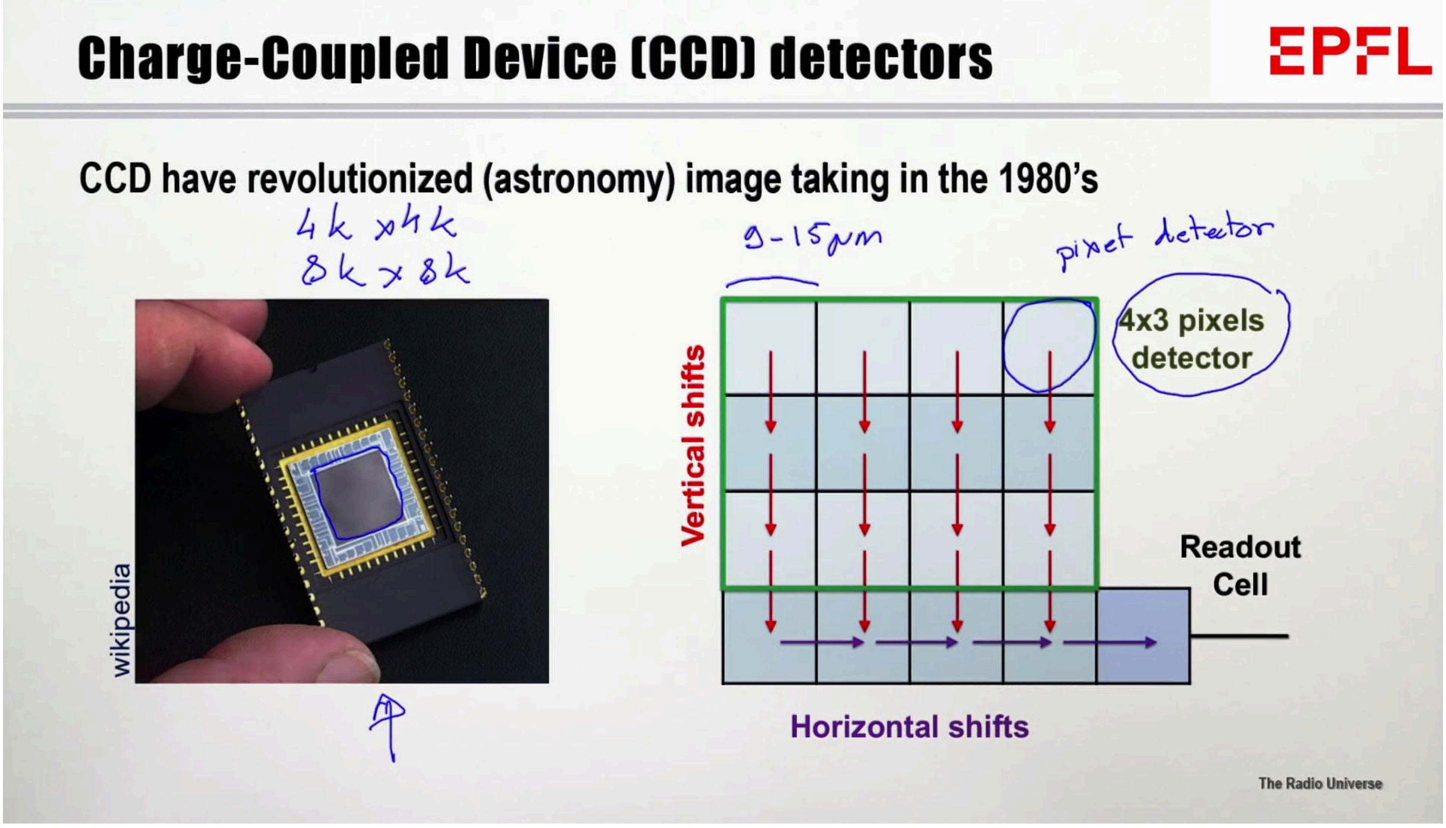


So what are the quantity we're defining to determine this efficiency. As I just say, going from photons to electrons cannot be done at 100 percent efficiency so only a fraction of photons are converted into an electron. So we're defining what we call the quantum efficiency that we usually write 'QE'. This quantum efficiency ‘QE’ will depend on the wavelength of our photons. Okay. So we write that ‘QE’ of lambda and so statistically our ‘QE’ of lambda we can write it as just the number of electrons detected measured by 'N', the number of photons emitted. Okay. So we can do this measurement. This is something we can do in the lab and we can then characterize our bucket detectors through the quantum efficiency ‘QE’ of lambda.

Notes

Summary

3m 32s

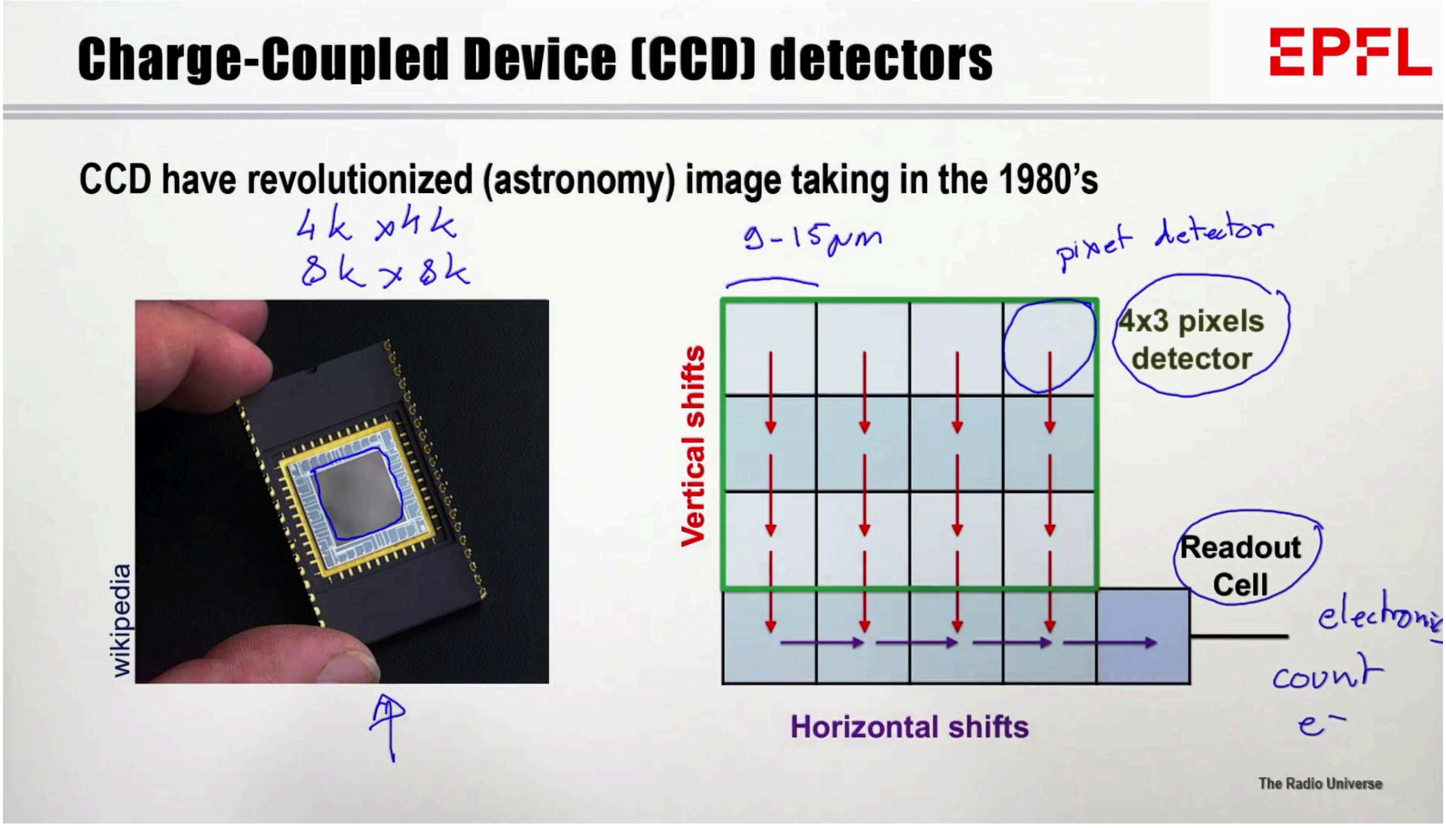


So when we detect light we also interested to see where it come from. So having just a single bucket detector is usually not enough especially if you want to make a picture of the sky or something. So there's been detectors that have been developed about 40 years ago that we call the Charge-Coupled Device and they're pretty much efficient and you can find them everywhere like in your smartphone or in a regular camera. And they've basically revolutionized astronomy image taking in the 1980s. So here we have an image of a CCD detectors where we have here an array of bucket detectors and around we have some electronics. So this array of detectors will work like that. Here we have a very simple schematic of such a detector which is made of four by three pixel. So each pixel is a detector so let's call it pixel detector. This typical size of such a pixel is a few micron. So typically we have size of 9 to 15 micron. So today typical detector size will be 4k by 4k, that means 4000 pixels by 4000 pixels. We can even make a larger detector today probably up to 8k by 8k detectors. This is now very common. The size of the detector will basically be limited by the size of the silicon wafer from which we have produced the CCDs.

Notes

Summary

4m 46s

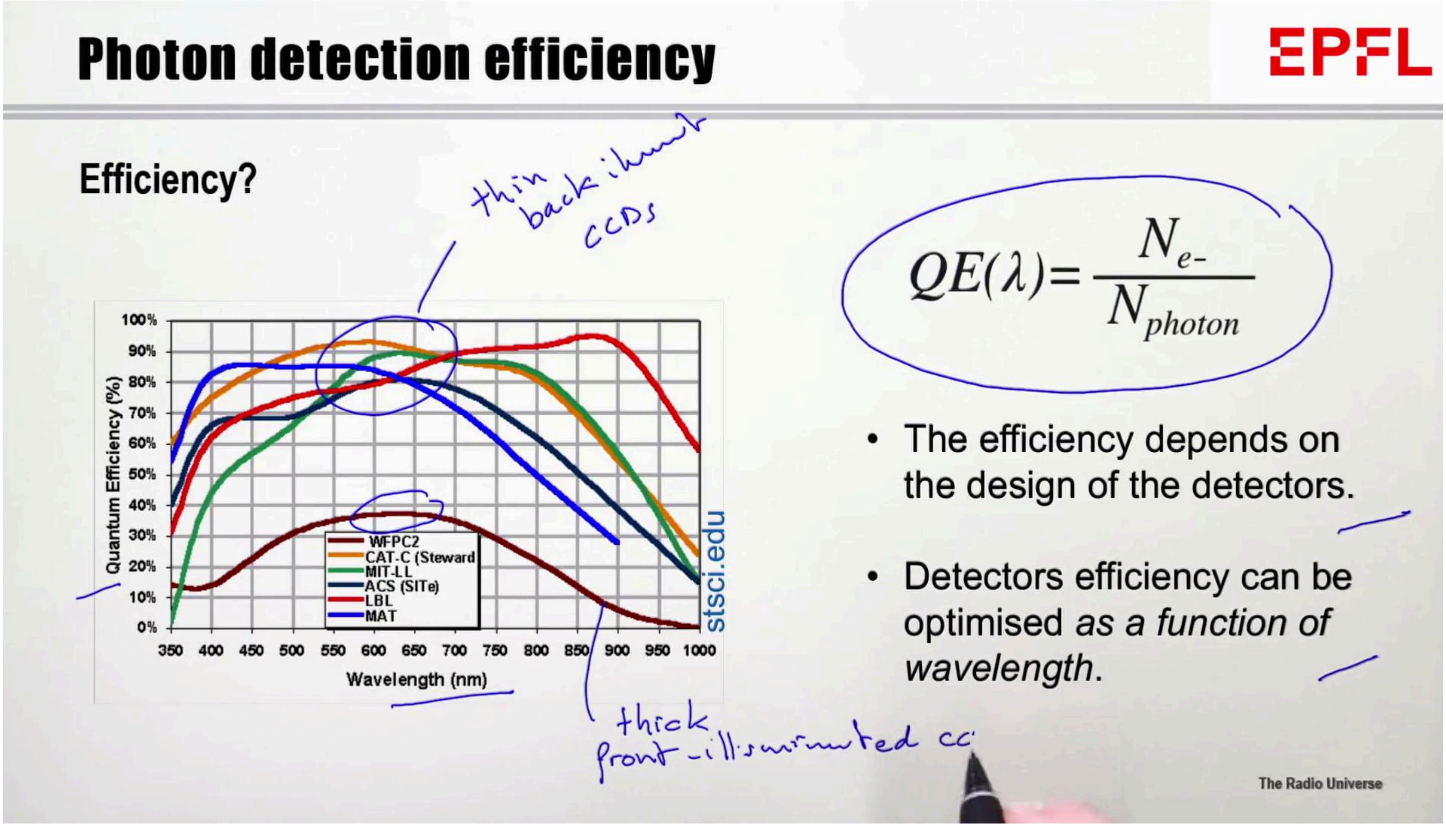


But now let's have a look of all we gonna count charges electrons charges into our detector. The idea is that we're gonna count the charges in each of the pixel detector in each bucket sequentially. So we're gonna have what we call a readout cell. Okay. So we have to move all our charges coming from the different rows into the readout cell. So the first step will be to move vertically the charge from one pixel to another pixel for each of the rows into the bottom rows which will be at the reading row. So we move first the charges vertically and then we move charges horizontally one by one so then in the readout cell we can count the charges that are coming from the different buckets. So here we can have some electronics that we turn that will count our charges our electrons. So in this way we can basically measure what was the flux received in each of the pixel detectors.

Notes

Summary

6m 54s

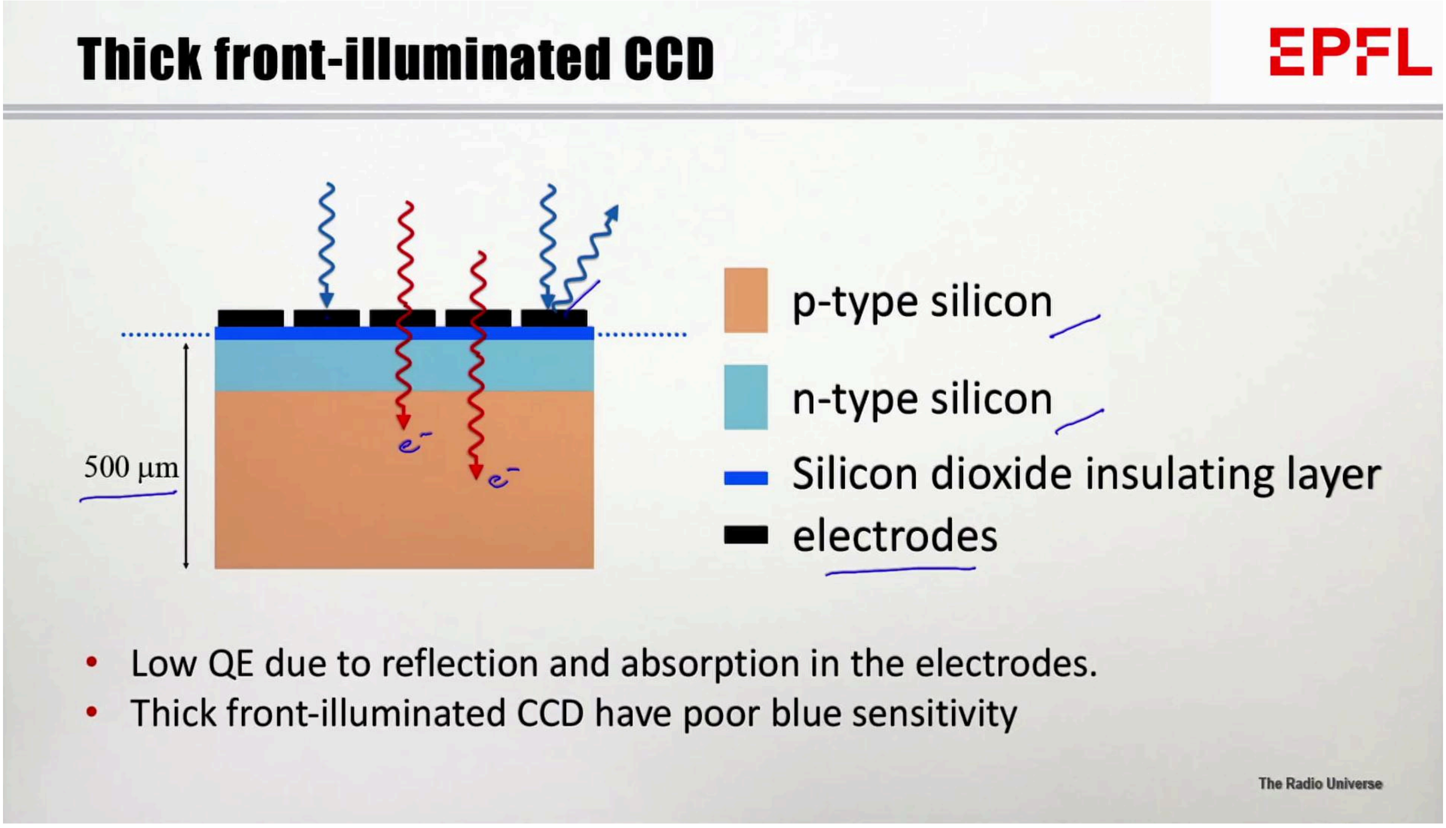


So what is the efficiency of such a CCD detector? Here we have a curve that shows difference value of the quantum efficiency as a function of wavelength where the wavelength is expressed here in nanometer going from the ultraviolet at 350 nanometer to the near-infrared at 1000 nanometer. So remember the quantum efficiency is a function of lambda so the quantum efficiency lambda depends on the ratio of the number of electrons measured counted by our detector divided by the number of photons received. So as we see the efficiency depends on the design of the detectors because we see we have different lines for different detectors and we also see that the detector efficiency can be optimized as function of wavelength. We have detectors that are optimized here like the red line to be more efficient at brighter wavelength and like this blue line here is more sensitive in the blue wavelength. We can see that we have two types of detectors. We have the one at the top and we have the one at the bottom. The one at the top are basically thin back-illuminated CCDs and the one at the bottom are an older version of it which we call the thick front-illuminated CCD.

Notes

Summary

8m 21s

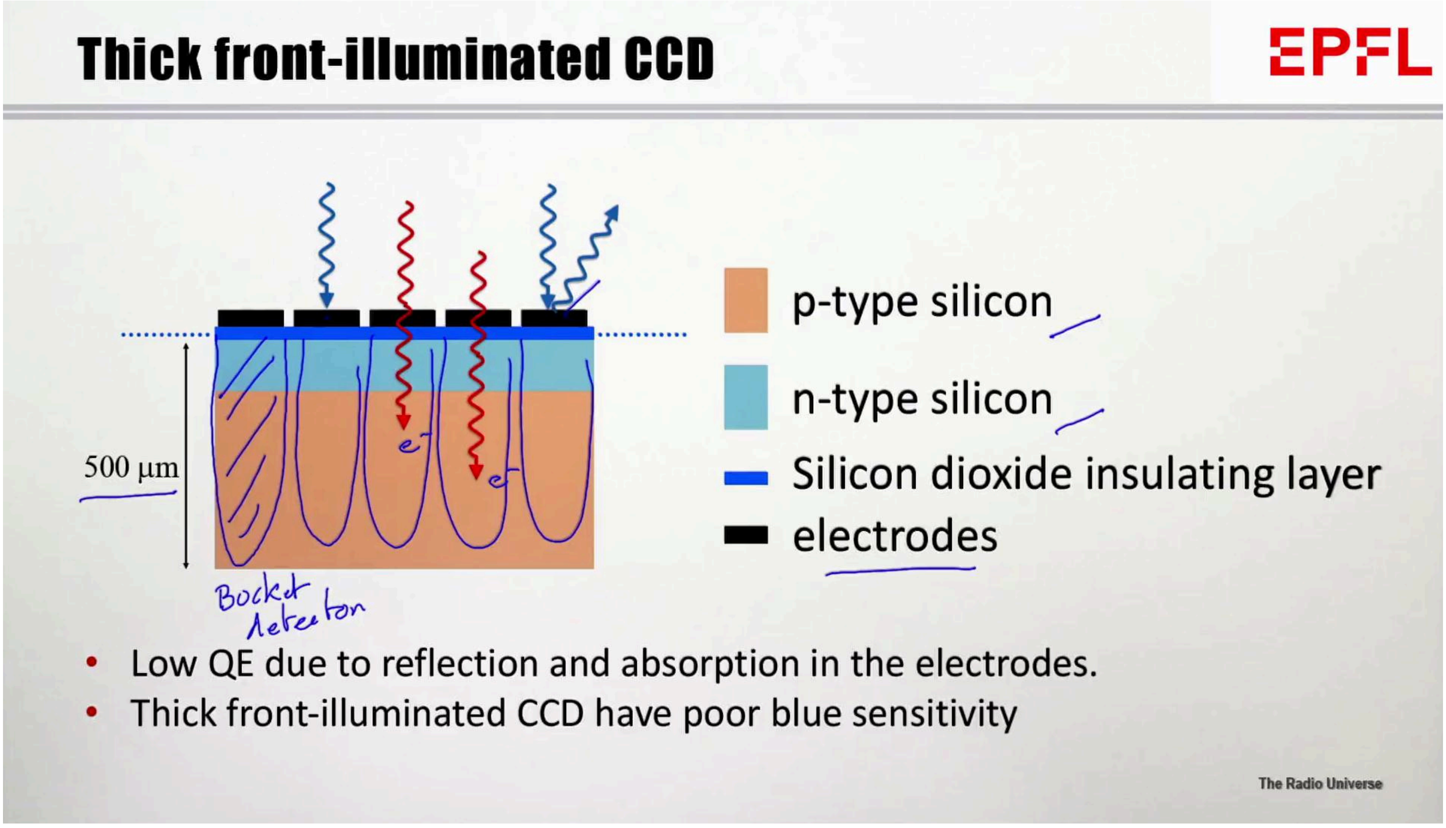


So what are the difference between this different type of detector? Let's have a look first at the thick front-illuminated CCD which were basically the first type of CCD detectors that were invented. So how does it work? So a CCD is made of silicon and we have two type of silicon; the p-type of silicon and the n-type of silicon that we are presented here. The thickness of the silicon is something like 500 micron. On top of the silicon we have a silicon dioxide insulating layer and on top of this layer we have some electrodes that are presented by these black rectangles. The light is coming from the top here and they're going through the electrodes through the silicon dioxide insulating layer and they end up being detected in the silicon and basically producing electrons. Of course, because you have some electrodes, you might have some reflection like here or you could have also absorption directly of the photons into the electrode. This will limit the quantum efficiency either due to reflection or absorption in the electrode. So that's not very good if you want to reach a higher quantum efficiency. So interestingly the absorption and the reflection of the electrode is more important in the blue.

Notes

Summary

10m 02s

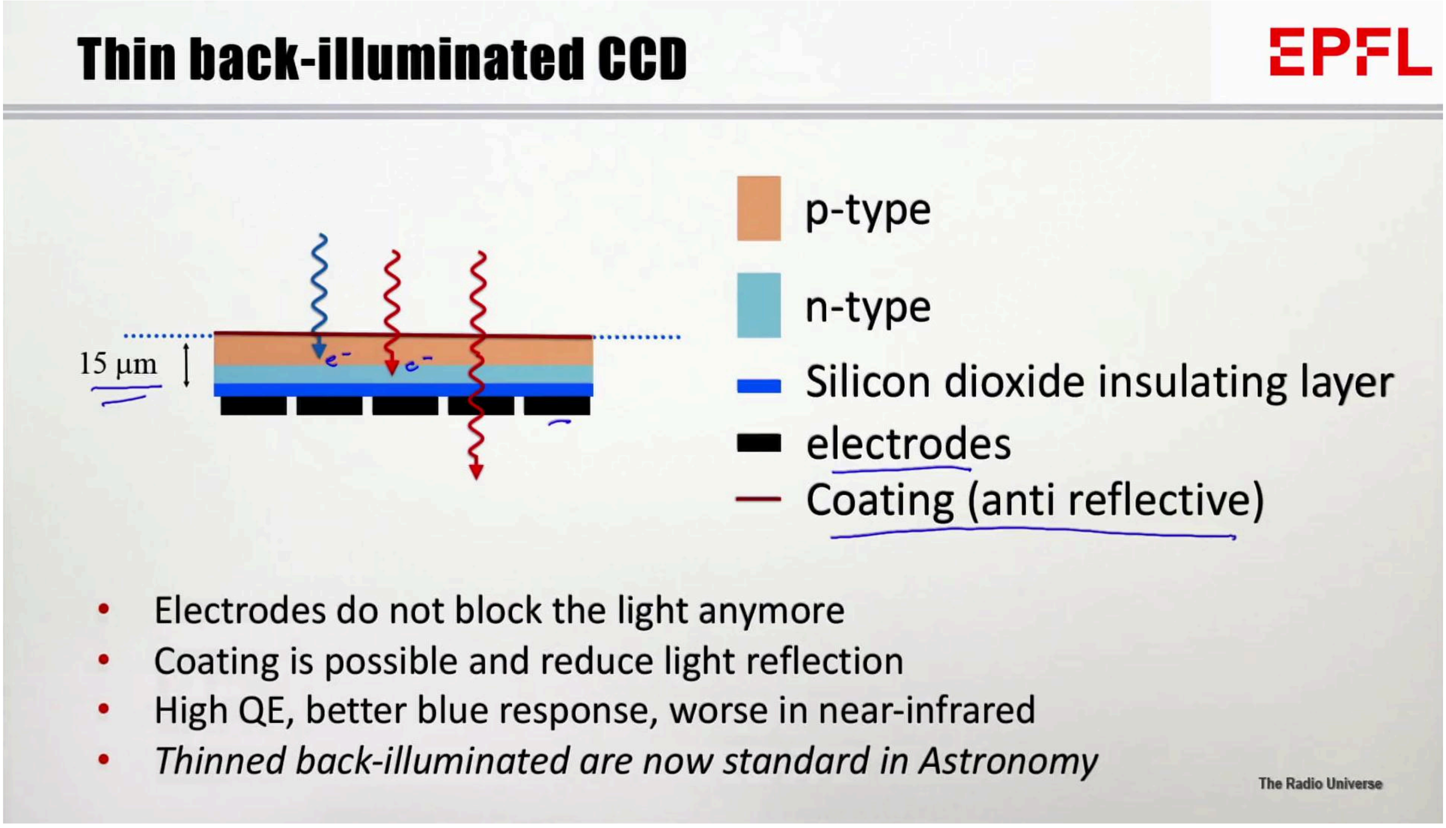


So that means that thick front-illuminated CCD have usually poor blue sensitivity. What is also very important to understand is that the charges will basically concentrate below each of the electrode so below each of the electrode it's where we have our bucket detectors.

Notes

Summary

11m 36s



So to improve those detectors engineers have been thinking of changing the way the CCD should work. So basically they rotated the detectors. They put the electrodes at the bottom and they also added what we call a coating layer which is anti-reflective. By doing that photons are then not anymore reflected by the electrodes and they go directly into the silicium and produce electrons. Except if you go to the very large wavelength closer to the near-infrared, if the size of the detector is very small then some of the photon will just go through the detector. So the good thing of thin back-illuminated CCDs is that they don't have electrodes on the top so electrodes do not block the light anymore so the detector is becoming more sensitive and you can also have this coating layer because now you have a very flat surface and then this anti-reflective coating layer will reduce light reflection as we will see. So all together you have a higher quantum efficiency, you have a better blue response, also might be worse in near-infrared if you make it the detector very small in depth. So ultimately thin back-illuminated detectors are now standard in astronomy and in many applications.

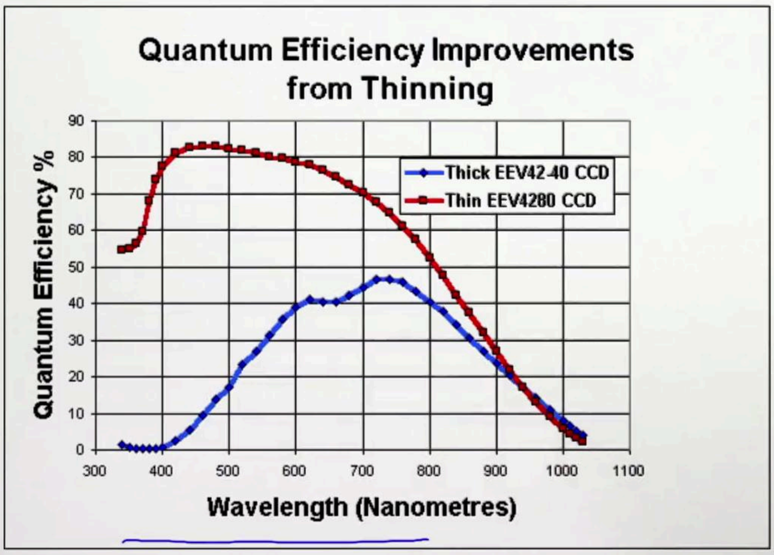
Notes

Summary

11m 57s

QE improvement with thinned detector

EPFL



Thinned CCDs are almost perfect detectors !

Remember:

Human eye QE is 1% at maximum

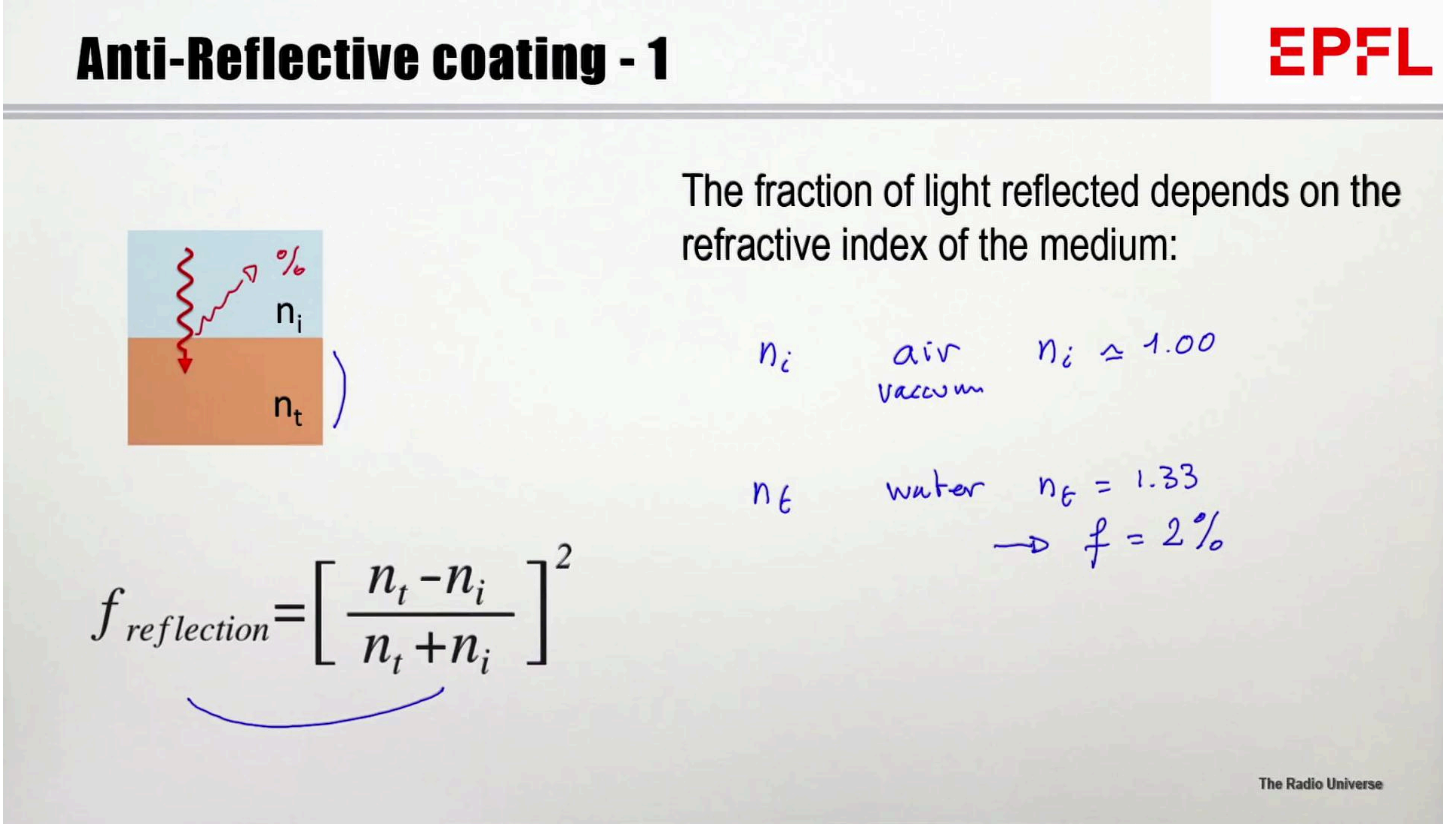
The Radio Universe

This plot is showing the ‘QE’ improvement going from thick detector to thin detectors. As we see here what you're gaining a lot is the efficiency in the blue side, you know, typically in the region from 300 to 800 nanometer and this is our two CCD detectors from 'e' to 'v'. So as you see thin CCD detectors are almost perfect detectors. We are reaching more than 80 percent quantum efficiency. And remember human eye quantum efficiency is only at the level of one percent at maximum.

Notes

Summary

13m 45s

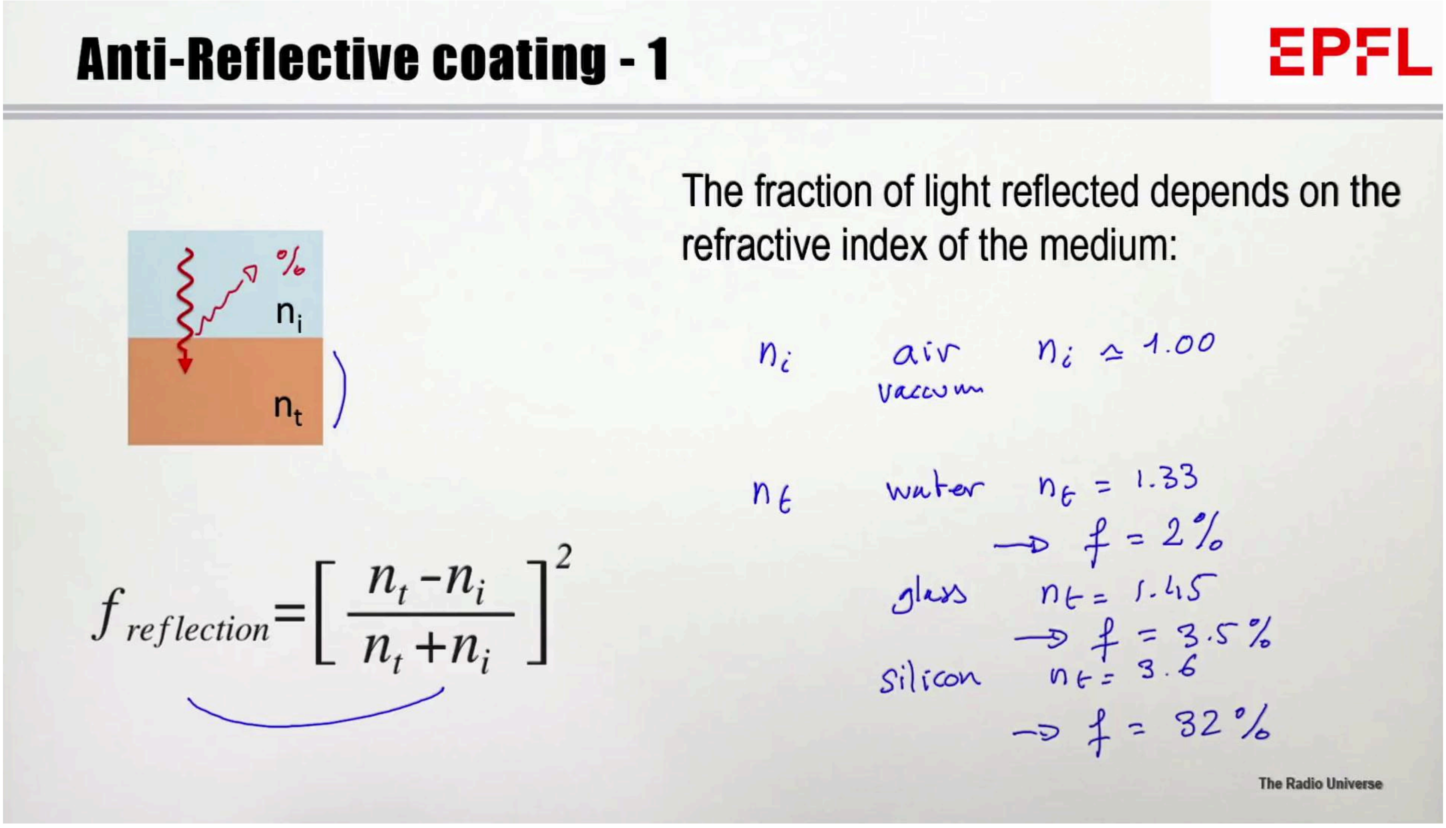


So let's come back to this coating issue. These anti-reflecting coating that are put on the silicon. Where it's coming from? Well, you have to understand or remember that the fraction of light reflected onto a surface will depend on the refractive index of the medium. So here we have a schematic. We have photons that go from the incident direction into a medium what we call a transmitted medium. Okay and, of course, you might have some of the light being reflected at the interface. So what is the fraction of the light reflected? Well, it will depend as we see on the refractive index and the fraction of reflection is defined here. So the fraction of reflection is the square of 'nt' minus 'ni' divided by 'nt' plus 'ni'. So 'ni' is the incident medium. For the air we have 'ni' which is about equal to one. That's also the case for vacuum. We have a similar index. I know what is the index of the transmittive medium. Well, we'll call it 'nt' and this will depend on the matter of that medium. For example, if we have water the index 'nt' is about 1.33 which means if you compute the fraction 'f' we can measure we can find a value of about two percent. So two percent of the light on the surface of water is reflected.

Notes

Summary

14m 28s

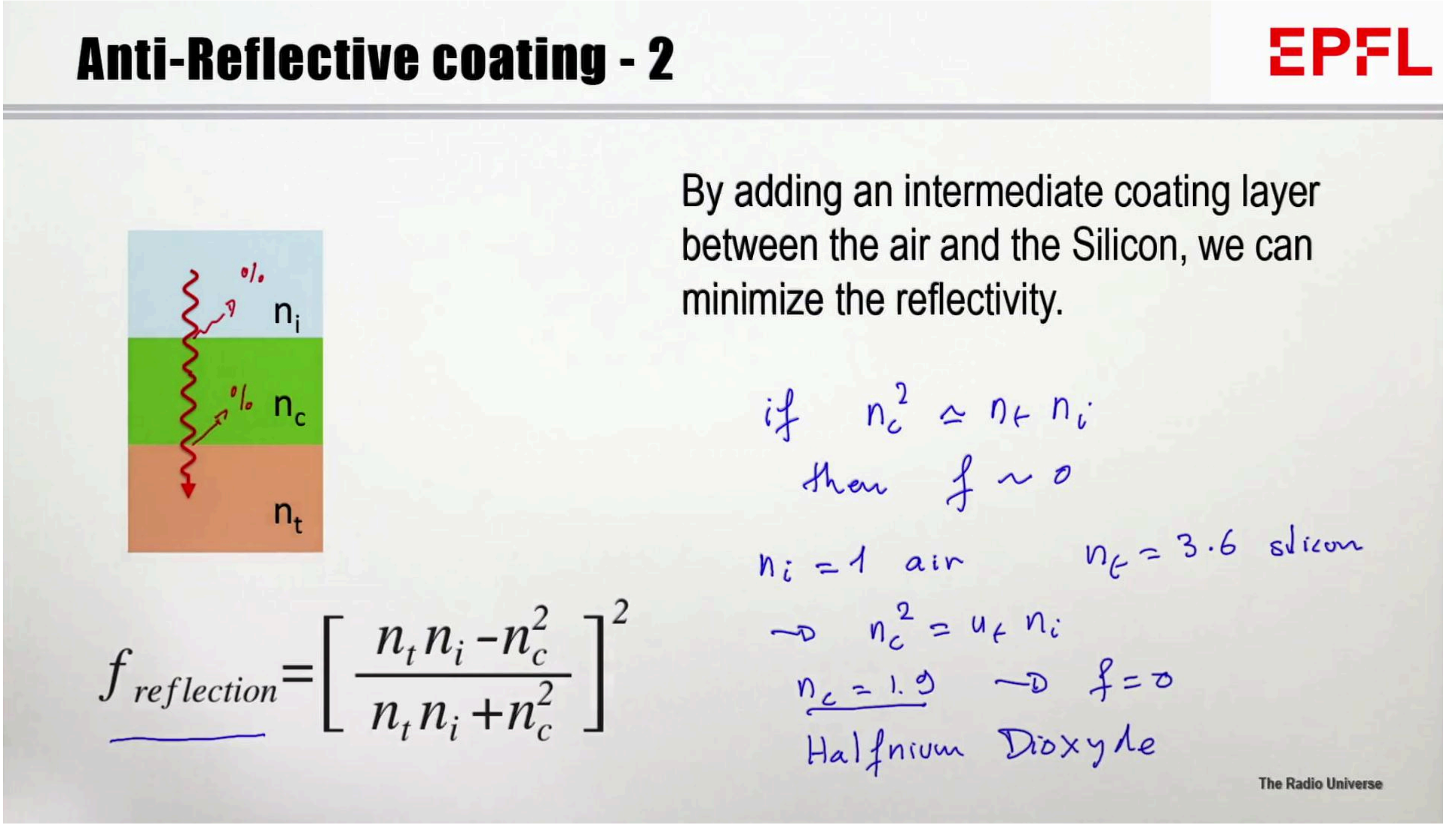


Now if you take glass, ‘nt’ is about 1.45 which means the fraction of light reflected is about 3.5 percent. This is not much. Now if we consider our silicon detector or CCD, 'nt' is much worse. It's much larger. ‘nt’ is about 3.6 and that means the fraction of light reflected is about 32 percent. So 32 percent of light eating silicon is reflected. That's not very good if you want to have a good detector. So that's why we want to put what we call an anti-reflective coating at the surface of the detector.

Notes

Summary

16m 48s



Indeed, by adding an intermediate coating layer between the air and the silicon in our case we can minimize the reflectivity. Indeed, the fraction of the light reflected if you have such different layer, the incident medium, the coating and the transmittive medium, the reflection will get smaller. The idea is to have values of reflectivity in this being closer and then the reflection here and here at the different layer will be much smaller. So the total reflective in fraction is written as the square of 'nt' times 'ni' minus 'nc-square' divided by 'nt' times 'ni' plus 'nc-square'. So what should we do to minimize the reflection? Well, we have here a difference. So if we minimize this term here then we will minimize the reflection fraction. So if we have ‘nc-square’ about or equal ‘nt’ times 'ni' then then the fraction ‘f’ will be about zero. So in this sense we're gonna minimize the reflection. So if we take our example where we have 'ni' equals one, that's the air and we have 'nt' equals 3.6, that's the silicon then we can compute ‘nc-square’ as 'nt' times 'ni'. So if we manage to choose 'nc' equals 1.9 then the fraction will be equal zero. If we use a coating layer of half neon dioxide we end up effectively with a refractive index of 1.9. So adding such a layer on the CCD will basically minimize the reflection.

Notes

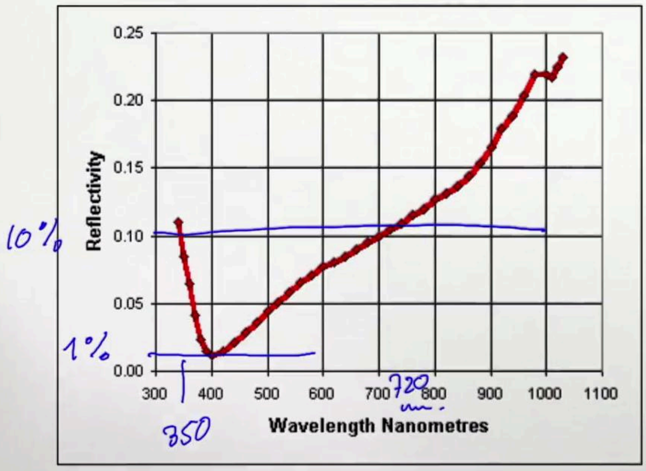
Summary

17m 46s

Anti-Reflective coating - 3

EPFL

Example of a anti-reflective coating for a CCD: reflectivity curve



The Radio Universe

This is the reflective curve of such a coating and we see here that, of course, the reflection will depend on the refractive index of the different components; the air, the silicon and the quoting and that might depend on the wavelength as we see here. So in this case we see that we're reaching a level of one percent of reflection at about 400 nanometer and it reaches value of 10 percent at about 350 nanometer and at about 720 nanometer. We have minimized the reflection on the detector.

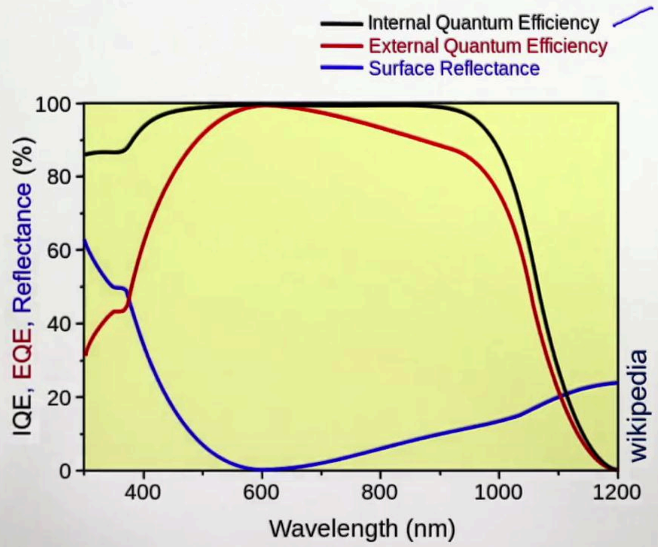
Notes

Summary

20m 38s

Internal and External QE

What is important, is the external QE (once reflection is taken into account):



$$QE_{ext}=QE_{int}.(1-R)$$

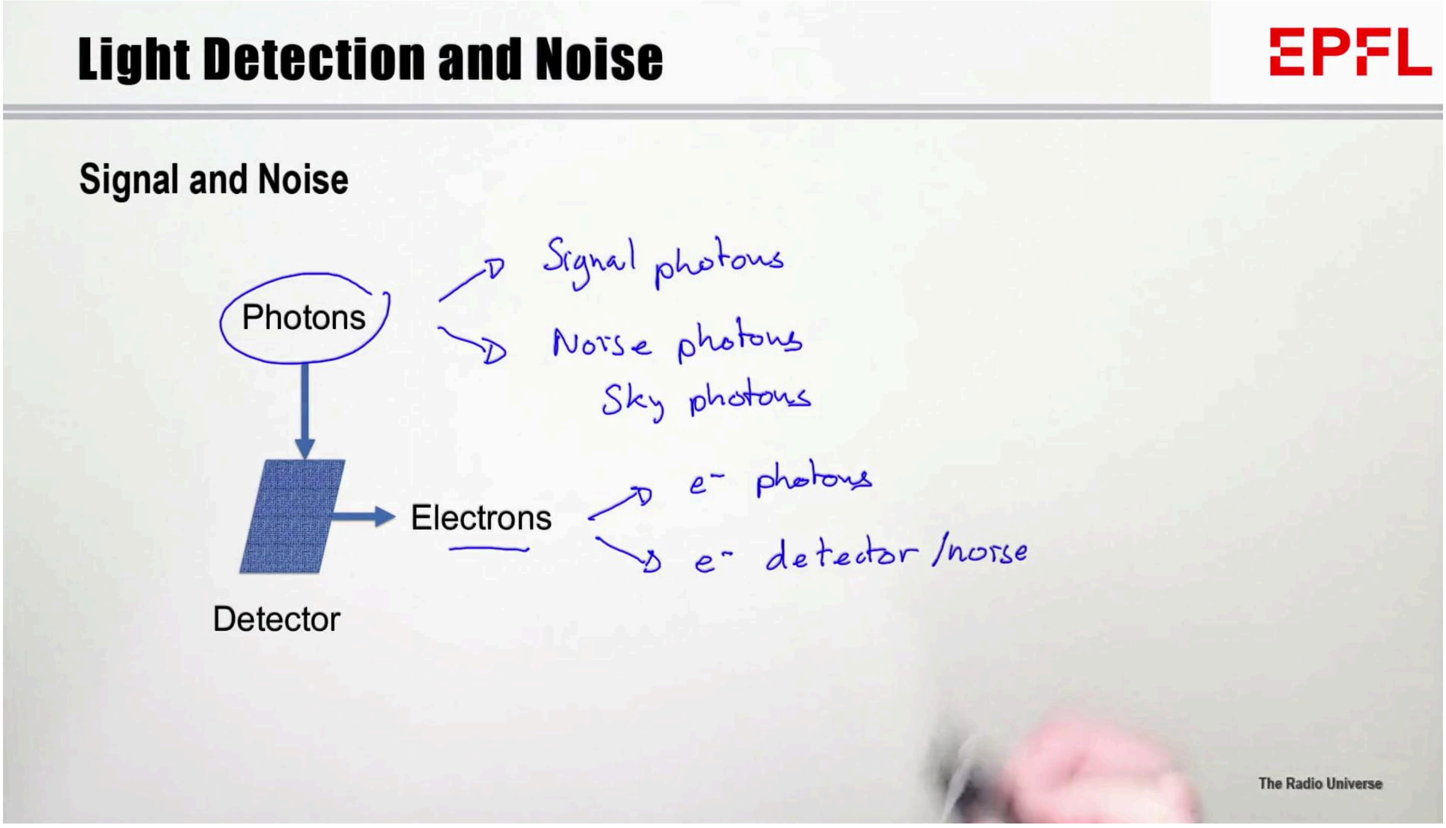
The Radio Universe

So ultimately what's is really important is what we call the external 'QE'. Here we have a couple of curves that are showing the different value involved here. We have in dark here the internal quantum efficiency that's really linked to how many photons we're converting into electrons within the detector but, of course, we have this reflectance surface that we try to minimize by putting this anti-reflective coating and we have the reflectance here expressed as a percentage by this blue curve and here's we see that we have chosen the coating which minimize the reflectance at 600 nanometer. And the final important curve is what we call the quantum efficiency the external quantum efficiency which is equal to the internal quantum efficiency which correspond here to the dark curve times one minus 'R' where 'R' is the fraction of the light reflected.

Notes

Summary

21m 33s

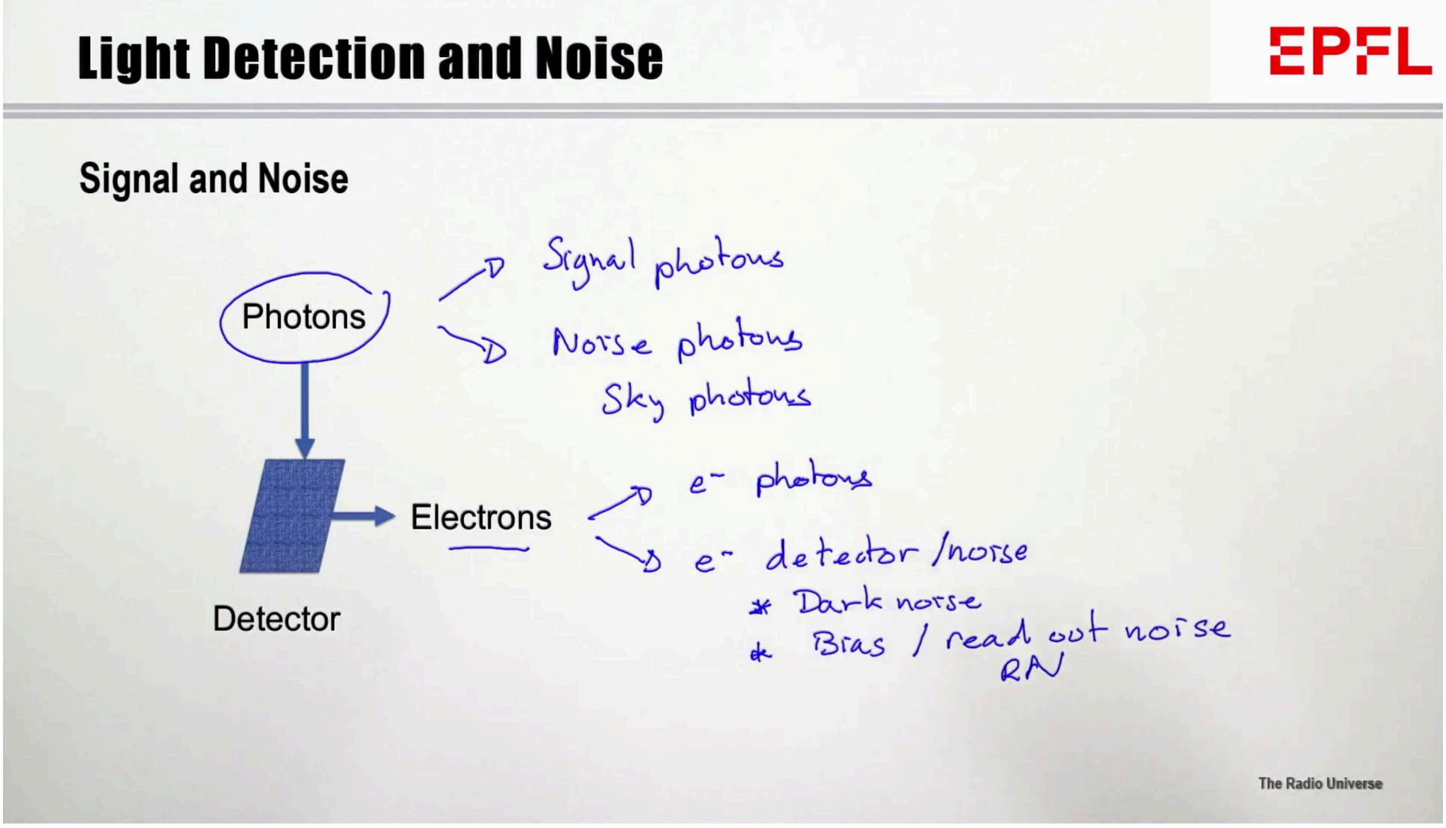


Right so now we've seen the process how we are gonna detect the light. We see it's important to minimize and to design a detector to be as efficient as possible. But efficiency is not everything. We have also to deal with possible noise. We have noise coming at different levels. We have noise coming at the photons level. Indeed, our detector might receive two things. It may receive what we call signal photons so that, for example, if we're interested to study the sky there will be photons coming from a galaxy or from a star but we can also receive what we call noise photons so that are photons that if possible we would like not to detect such as sky photons, that is, photons that are produced in the atmosphere, for example, by reflections. Then we're gonna detect in our detector in our bucket detector those photons and those will produce electrons. So the electrons that will be measured by our system there will be two kind. There will be the electrons that are coming from the photons directly through the quantum efficiency curve and we have also some noise electrons. Okay that will be produced by our detector intrinsically. So we have photon that are coming from our detector and those are basically noise electrons.

Notes

Summary

22m 51s

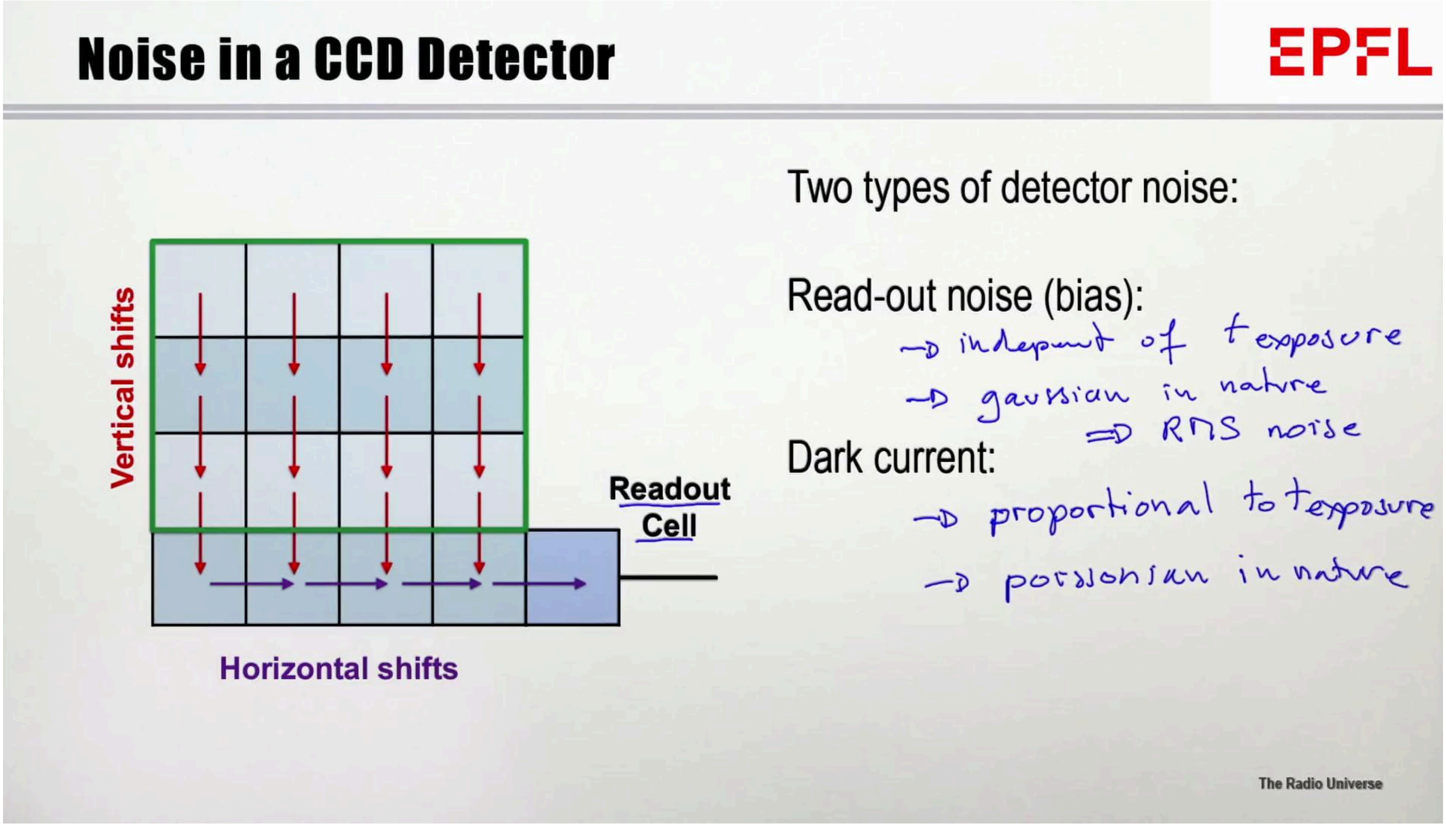


We can identify two types of detector noise. What we call the dark noise and what we call the bias or the readout also written RN. So let's understand the origin of this detector noise.

Notes

Summary

24m 48s

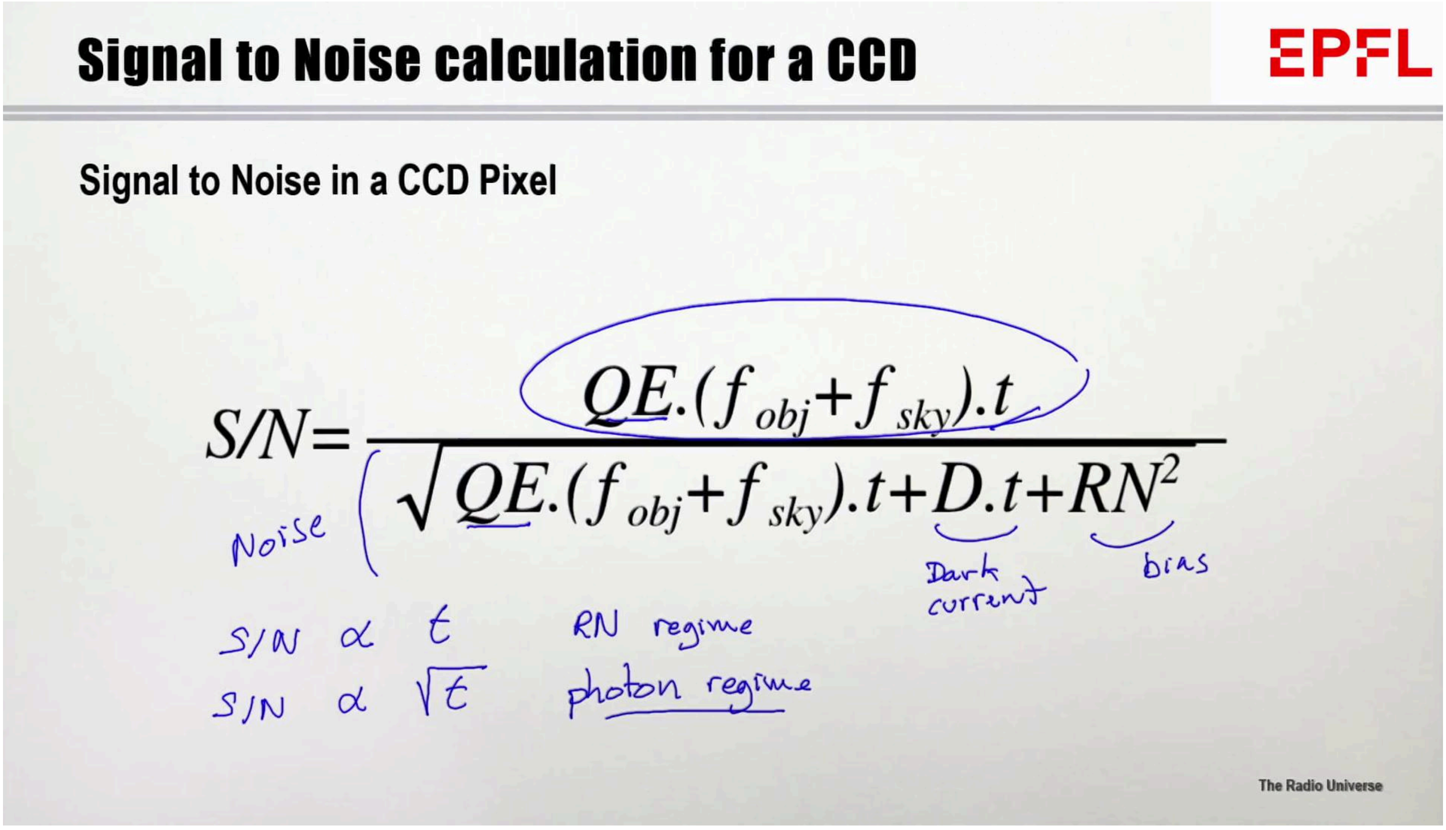


So to understand this detector noise let's come back to the very simple schematic of our detector. So as I said there's two type of noise. First one is what we call the readout noise. The readout noise is basically produced at the readout level either in the readout cell or in the electronics of our detector. Because this noise only come at the readout time, this is independent of the time of the exposure. Right. And because it's a white noise electronic noise this is a Gaussian in nature and so we define usually what we call as an RMS noise. The dark current will be proportional to the exposure time and it will be Poissonian in nature. Okay because the dark current will produce at the level of each cell and the longer the exposure time, the larger the number of electron produce through the detector.

Notes

Summary

25m 07s

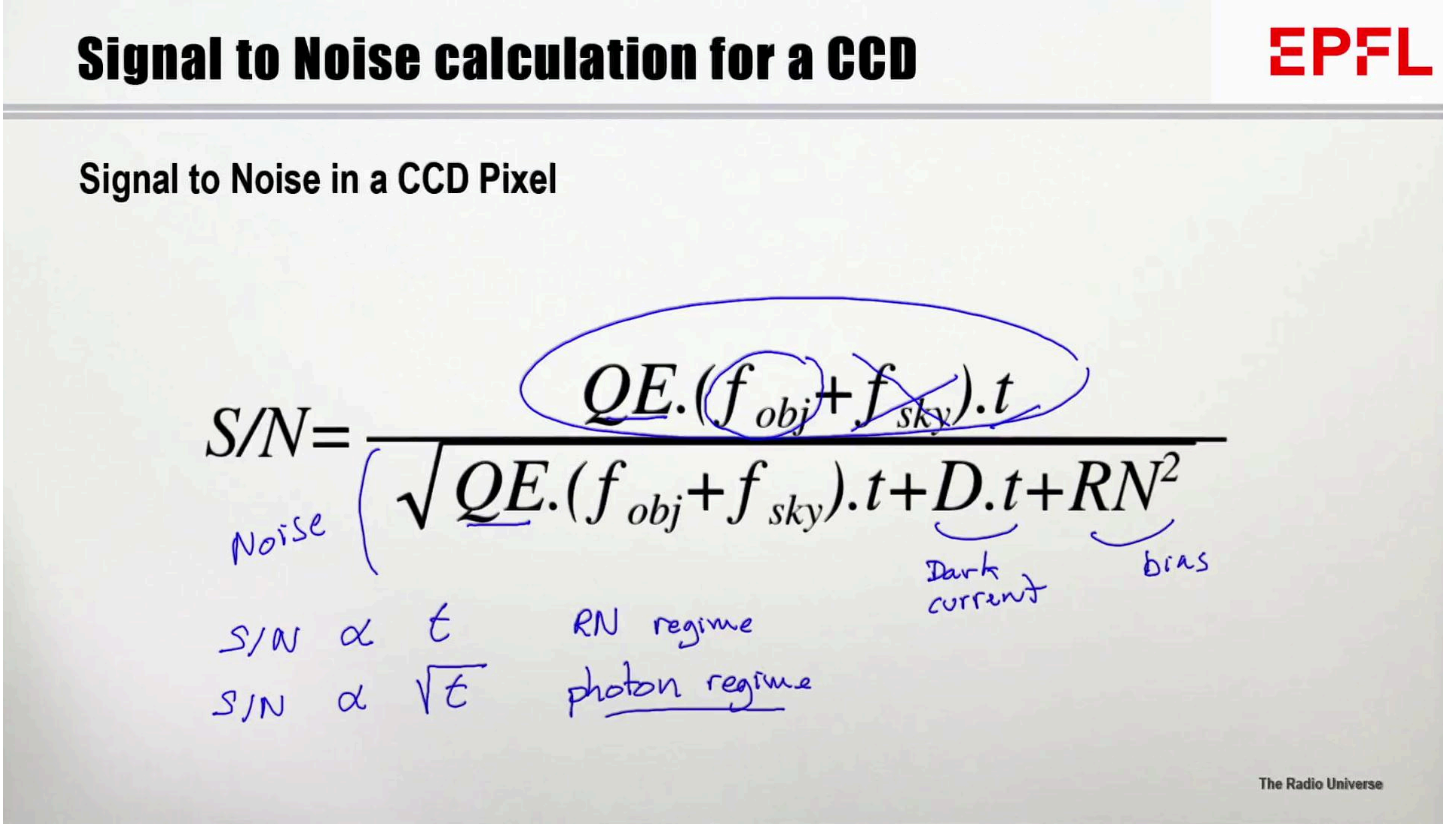


So we can summarize the our signal to noise for CCD in the following expression. So at the top here we have our signal and at the bottom here we have our noise. We can see we identify the quantum efficiency here which basically transform the number of photons into a number of electrons so our signal to noise estimate is given as a signal to noise expressed in number of electrons. The signal is proportional to time as well as the dark current but this term correspond to the bias which is independent of the time of exposure. So we can see we have two regime. The first regime is a signal to noise that will be proportional to time. This will be the case if the bias is dominating this term and then we have signal to noise but is proportional to time only and that what we call the readout regime. And we have another regime where the signal to noise will be proportional to square root of time and that's we call the photon regime. So a detector is usually used in the photon regime. Okay. Why because small exposure time will be a readout regime and long exposure time where this term will dominate in front of the bias, it's what we call the photon regime.

Notes

Summary

26m 19s



So it's better to be in a photon regime because it's where we have basically gone over the readout regime and so we have obtain a larger signal to noise value. Here I represented the signal as the sum of the flux coming from the object and the flux coming from the sky but in general, when we're interested to detect the flux of one object usually we will not take the flux of the sky here and just only consider the flux of the object. But that's a detail for signal to noise calculation.

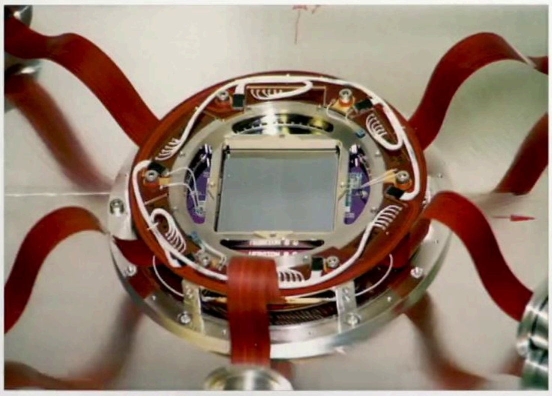
Notes

Summary

28m 09s

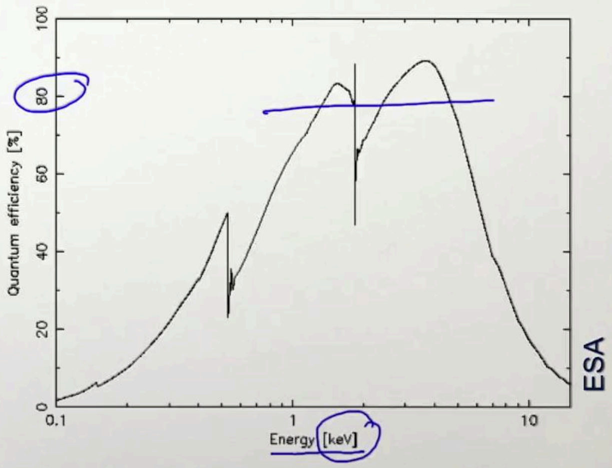
X-ray CCD

CCD can also be used for detecting X-ray photons



XMM-Newton X-ray CCD

Dec 1999

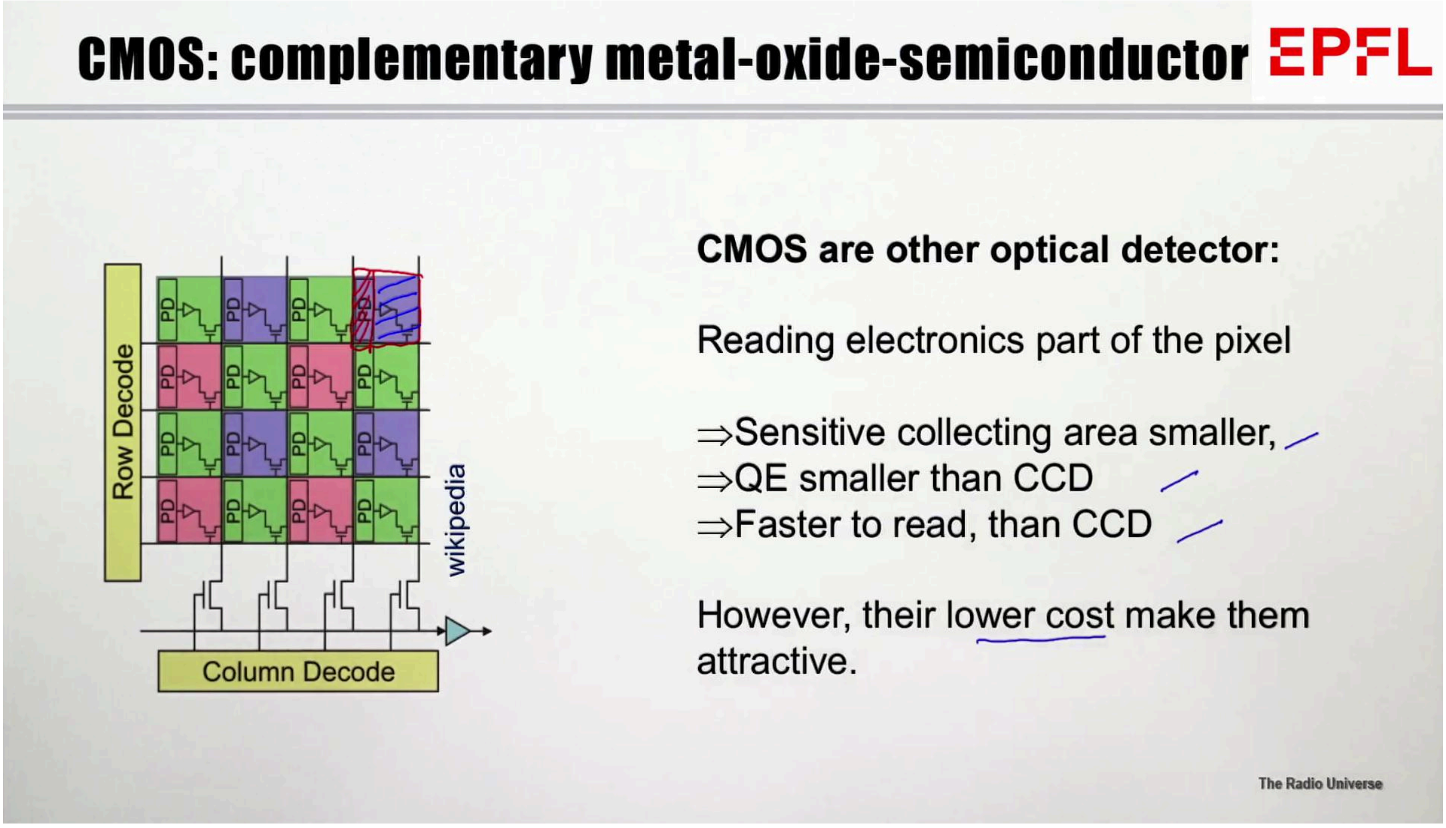


So not only we can detect the photons at visible wavelengths and that's the role of the CCD detector, we can also use CCD detectors at higher energy so photons coming, for example, in the X-rays. And we have been designing engineers have been designing X-ray CCDs. So CCDs that are sensitive at energy level of kilo electron volt typically so ranging typically from one to ten kilo electron volt which correspond to the X-ray domain and we have available detectors that are also reaching more than 80 percent quantum efficiency at about two to five kilo electron volt. Here we have a picture of such a detector, an X-ray detectors an X-ray CCDs that has been put on the XMM-Newton space telescope that was launched in December 1999.

Notes

Summary

28m 56s



There exist also other type of visible detector which are called the CMOS detector. CMOS means Complementary Metal-Oxide Semiconductor. CMOS are other optical detectors and the difference between the CCD and CMOS is essentially coming from the fact that each pixel have only one part that is sensitive to the light. That's what we call the photodiode and that's the sensitive element and the rest of the pixel is basically corresponding to the reading electronics. So that means the sensitive collecting area is smaller which mean all together the quantum efficiency is smaller than the CCD because for a CCD the full pixel would be sensitive to light. However, because the electronic is on each of the pixel you're gonna read much faster the CMOS detector compared to a CCD. The other interest is their lower cost which make them very popular so in most of the cell phone in your smartphone you more have CMOS detectors than CCDs.

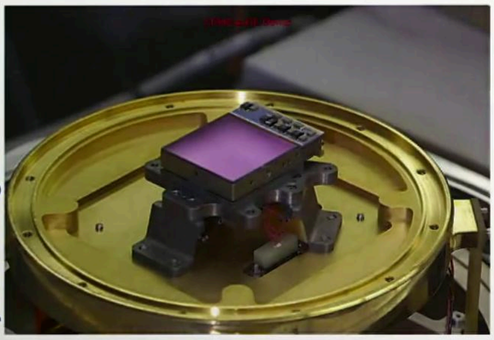
Notes

Summary

30m 12s

Infra-Red detector

EPFL



jwst.nasa.gov

JWST/NIRcam detector

2021

Infra-red detector can cover wavelength from ~1 micron to ~10 microns.

Silicon detector are limited to ~1 micron.

Use a different material sensitive to lower energy e.g.:

- Mercury Cadmium Telluride (HgCdTe) – High QE
- Indium Antimonide (InSb) – only 1-5 micron

The Radio Universe

Another type of detector is what we call the infrared detector. Infrared detector can cover wavelengths from one micron to 10 micron and here we have a picture of a detector in near-infrared that will be put on the JWS Telescope on the NIRcam camera. This telescope should be launched in 2021 and it would be very sensitive to infrared wavelengths. However, because silicon detector are limited to one micron in terms of wavelengths of photons, we need to use different material to be sensitive to lower energy photons. So typically we use two type of material, either the Mercury Cadmium Telluride. This is a very effective and very sensitive material that covers typically from one micron to 10 micron. It has very high 'QE' and then it's so very much used. Other type of material like Indium Antimonide is also used to as infrared detector but it only cover one to five micron and it's a bit less sensitive.

Notes

Summary

31m 51s

As we have seen, high energy photons are detected considering them as particle. To collect them we use a bucket in which a fraction of the photons received is converted into an electron following the so-called quantum efficiency. In particular, we underline the importance of the anti-reflective coating we put on the surface of the detector which is key to maximize the overall detection efficiency. Then some electronic counts the number of electrons in the bucket allowing to quantify the amount of photon flux received. Not all the electrons counted are coming from astrophysical objects of interest so a number of processing will be needed to extract the information from the measurement. Finally, we have seen that different detectors are used for different photon energy levels and we saw with concrete examples for X-ray and near-infrared detectors. For the next time, we will look how to detect low energy photons.

Notes

Summary

33m 22s