Indian Institute of Technology Kanpur

National Programme on Technology Enhanced Learning (NPTEL)

Course Title
Optical Communications

Week – VII
Module-III
Detection of light

by
Prof. Pradeep Kumar K
Dept. of Electrical Engineering
IIT Kanpur

Hello and welcome to the moke on optical communications. In this module we will talk about detecting light which of course, forms the major component of an optical communication system, because you who would have taken the electrical signal which would be representing some information and you would have used an optical transmitter to convert this electrical signal into an optical signal.

And this optical signal would have travelled from the transmitter side, you know through the optical fiber, there might be additional DWM components through which this optical signal would have passed through. But as long as it remains optical you cannot extract the information back, unless you convert this optical signal into an electrical signal from which you will perform the extraction of the information.

So the objective of the receiver the first task of the receiver would be to extract the electrical signal from the optical signal okay. So how do we perform this function of converting the optical energy into electrical energy is the subject of detecting light. So when we detection of light what we mean is conversion of the optical energy which presumably carries some information onto the electrical signal.

So we of course, have chosen it to electrical signal you can in principle choose it to convert to any other energy, but we know that we have been working with electrical signal. So the, our objective would be to convert optical energy to electrical energy only, and any such conversion transducer can be thought of as a photo detector okay. Photo detectors simply mean that they will convert the optical energy into a suitable energy.

In our case this suitable energy form will be electrical if for example, you choose to convert this into a thermal energy, then this can be done by what are called as thermal photo detectors, they will work by the principle of absorbing light in the form of photons right. So light travels, a light consists of photons in the quantum sense, so it will absorb these photons and then convert this absorbed photon energy, because once you absorb photons you are gaining some energy.

And this energy will be converted into the heat energy of a particular material okay. This heat energy of course, can further be converted into an electrical energy right by putting up a digital thermometer in the sense that you can perform a digital thermo, digital detection of the thermal energy, and then use that for extracting the information. These thermal detectors have a very wide bandwidth, unfortunately they suffer from extremely low sensitivity that is to say, they cannot detect optical signals which are low in power okay.

Because they require substantial amount of optical energy in order to convert that into the thermal energy, these are not the ones that are preferred for optical communication system. So what exactly do we use, what kind of detectors do we use in optical communication system, well these are all the semi-conductor diodes okay. So a simple diode such as of PN junction, you know when you reverse bias a PN junction you will know that from your electronic score such that there will be a depletion layer which consist, which if formed between the P and the N type junctions.

And the amount or the width of this depletion layer is controlled by the reverse bias that you are going to apply. So once there is a depletion layer which mainly consist of immobile ions right, which causes an electrical field between them, if there is a photon which falls on this depletion layer, then it can create an electron hole pair okay.

So this photon which falls on the depletion area that photon can be absorbed by the semi-conductor material and then intern convert that absorbed photon into a electron hole pair, which are then, you know drifted apart in opposite directions because of the inbuilt electric field which the depletion layer provides.

This is the fundamental way in which semi-conductor materials are used for photo detection. And we will look at couple of those photo diodes okay, most commonly used PIN photo diodes and there are more sensitive APD photo diodes, APD itself is avalanche photo diodes, so we might simply call them as APDs okay.

So before we begin, let us actually look at what makes a good detector, I mean if I have to use a detector for a 10gbps communication system versus 100gbps communication system, there have to be certain characteristics of this photo detectors that are important to me right. So one would obviously be if I have to increase the bit rate, I know from my system design part I, that there is something called as a rise time associated with the photo detector right.

It is essentially the response of the photo diode to a step optical input okay so if there is sudden change in the optical power will my electric signal in the form of a current be able to track this sudden change or how slowly it changes over it state is determined by the response time of the photo diode.

So if I want to send signals at a much faster rate you know increase the bit rate then I have to minimize this rise time of the photo diode, right. So one of the important things that I am looking for in a photo diode circuit is how fast it can respond to the optical changes, optical power changes how fast it can respond.

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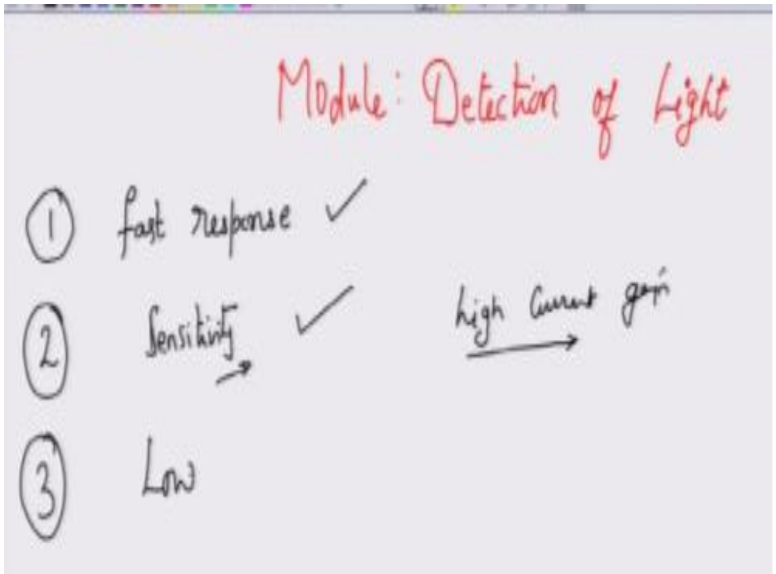

Such characteristic is related to the bandwidth of the photo diode the larger the bandwidth the faster will be the photo diodes so fast response is perhaps the first and foremost important criteria for optical communication based photo diodes I mean in some case where you do not require this fast response well you can use different materials but in optical communication systems especially at very high bit rates we require a fast response from the photo diode.

So if all everything else we have taken care of may be know we have minimized the rise time of the transmitter we have chosen excellent fiber with almost zero dispersion, right and therefore minimize the fiber rise time but then if we use a very bad photo detector which is a very slow photo detector there is all the advantages that we have gained by optimizing the transmitter and the fiber is gone.

So in order to avoid this I need to use a photo diode which is fast enough, so it can respond to very high bit rate and very high bit rates it can support very high bit rates in the form of changing optical powers right, so every quickly it has to track the changes in the optical power so that is one of the major characteristics that you are looking for when you are buying a photo detector or you are designing a photo detector circuit for optical communication system.

The second characteristic that you are interested is to say what could be the sensitivity of the photo diode, by sensitivity we mean that what is the optical input power, minimum optical input power that is necessary in order to cause a certain current in the photo diode, okay. So if my photo diodes if I have a choice between two photo diodes one whose minimum optical power requirement is -30DBM that is 1micro watt.

Or the other one which can know go down and measure up to -60 DBM which is 1 Nano watt clearly the second photo detector which has -60 DBM sensitivity will be preferred over the first one, of course there are certain trade off that you have to take care of if you lower the sensitivity too much then any instabilities any small changes in the optical power can be amplified or can be essentially detected as a signal.

So there are some problem associated by making the sensitivity too low something that we will talk about it when there are situation arises, okay. For our current module and know as I use of photo detectors as a in functional block of optical receivers fast response as well as sensitivity are the two most important criteria, okay. So sensitivity is associated with a high current gain as we said photo detectors work by absorbing optical energy in the form of photons.

And then convert that into electrical signals in the form of a current, so you want a low optical power as the input okay but at the same time you want that low optical power to be concerted into a very large amount of current, so you want a very high current gain for your photo detector and that of course is one of the side characteristic which is the result of having the sensitivity along with you.

So these are essentially two main characteristic that you are looking for from the signal perspective, now it is not just that a photo detector circuit simply converts the optical energy into electrical energy, it does so while it does this conversion it will also add the certain amount of noise, noise is a very important topic for photo diodes photo diode circuits or photo detector circuits.

Because noise comes from the way you package a photo diode the way you put the leads for your you know wires to take out the electrical current the load resistor which you are using what is the photo detector connected to what is the next stage of the amplifier that is connected to the photo diode all these things matter, okay. Every component out here will give enough amount of noise.

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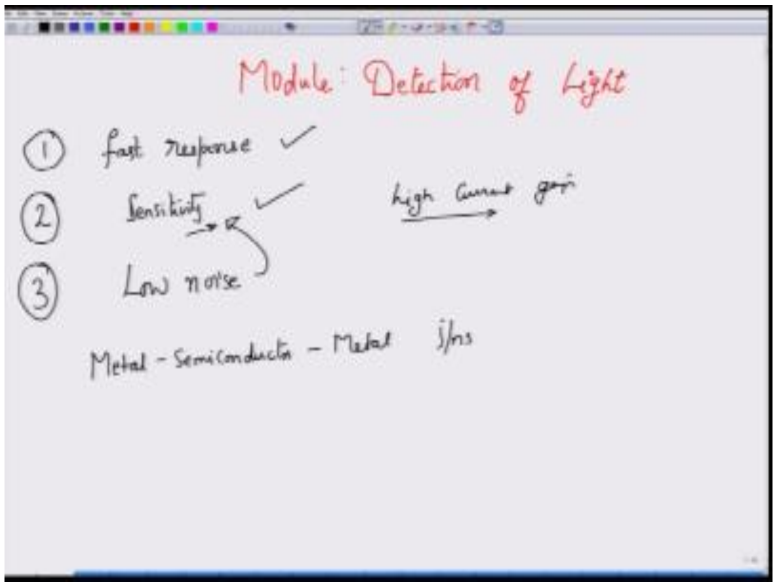

So one of the characteristic that you want from a photo diode is that it must add very little amount of noise. It must add very little amount of noise, okay so low noise is one of the important criteria from the noise perspective because if my photo detector adds very low amount of noise then I will be able to take the signal optical signal at very low powers yet I have sufficient signal to noise ratio at the output in ordered for me to detect information sitting in my desire signal, okay.

So it has to be low noise and this low noise condition coupled with sensitivity that is the sensitivity is you know the lower optical power, so coupled with these two is a very important rate of that you have to take care when you designing a photo detector circuit. What we normally do in order to improve the response of the photo detector is that, we use what is called as metal semi conductor there are many techniques these are the most common ones, so you use a metal semi conductor metal junctions. We know that metals have a large conductivity right.

So if the semi conductor observes photons and converts them into electrons then if you a metal then these electrons can quickly jump over to the metal side and then constitute a nice current. So you get a high gain current gain as well as the response basically becomes very fast, because an electron travelling through a semi conductor device will have a slower velocity compared to this same electron travelling through a metal because of the abundance of this electrons. So it actually improves the response so these are called as MSM photo detectors.

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So this basically improves both band width as well as the current gain so it has both high band width as well as high current can gain large band width and large current gain. The other technique that we normally use is what is called as this is even more common than the first one, is what is called as separate absorption and multiplication detectors, okay this principle is very interesting it simply says that you first have separate layer for absorbing optical power, so optical power when it falls on the photo detector there is a region which simply absorbs, okay.

And generates what are called as primary electron whole pairs or primary photo carriers, these primary carriers will then go and be collected into another region called as multiplication region.

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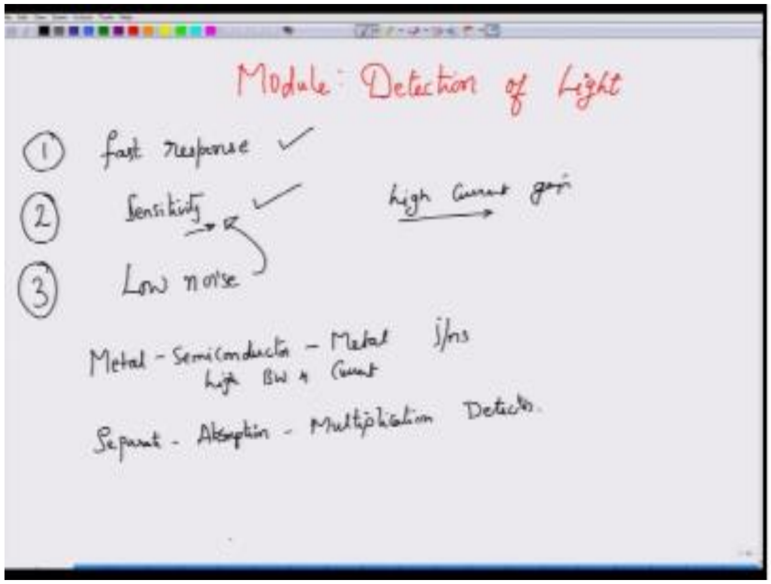

In this multiplication region each of the primary electron whole pair which is collected there will bombard with the existing lattice in order to generate even more electron whole pairs, so there is some sort of a secondary electrons which are being generated as a result of the primary electron whole pairs which have come from the optical input, okay. So the second region where in this ionization is happening you know the many more electron whole pairs are generated by the impact ionization which can quickly lead to what is called as avalanche effect and hence very large currents, okay flowing through the photo diode is a very important characteristic for low sensitivity optical detection.

So if you are detector has to work at say -110 dpm you can imagine how small that optical power is you want to use this characteristic. In a more general sense this characteristic is called as a photo multiplier and photo multipliers are also used in the visible range of optical communication so in the visible range when you are using then you use photo multipliers but when it comes to optical fiber communications where the frequencies are in the infra red meet infra red you will be using these photo detectors, okay semi conductors, photo detectors.

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The commonly used same photo detectors the separate absorption multiplication photo detectors are made out of Indium Gallium Arsenide and Indium phosphide hetero structures, okay hetero means different structures are essentially the layers of photo detector circuit, okay. The characteristics of Indium Gallium Arsenide is different from the characteristic of Indium phosphide and these two are sandwich the Indium Gallium Arsenide is sandwich between Indium phosphide layers, okay so this is called as a hetero structures and these are the once which are commonly used for photo detection.

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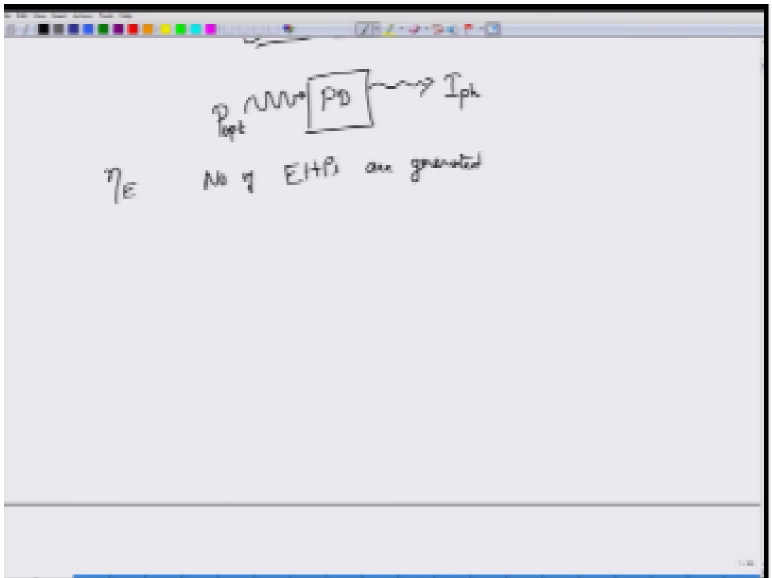

Now this was just probably and a very simple introduction to photo detectors we have not put down the matrix of a photo detector, right. So I have a photo detector or a photo diode, okay from an external black box point of view3 I will apply some optical input power to this, okay so we apply an optical input power to this, then what I get at the output is a photo current Iph okay. there is something called as quantum efficiency and this quantum efficiency is denoted by η.

And I have used another subscript E just to denote this as the external quantity external means that I have design my photo diode I do not have accesses to the internal working of the photo diode someone has given me a photo diode I am just using that one in my circuit all I am interested is to see what would be the fraction of the optical power that is observe by the photo diode and converted in to electron whole pars.

Please remember that this particular matrix is used commonly for the PIN photo diodes that is because there is no secondary electron whole pare generation okay. So this is the primary electron whole pares in the Pin detectors therefore this external quantum efficiency is what would be normally use okay. This external quantum efficiency tells you the number of electron whole pares that are generated okay. That is are generated because of observing the optical power let us consider a typical photo diode okay.

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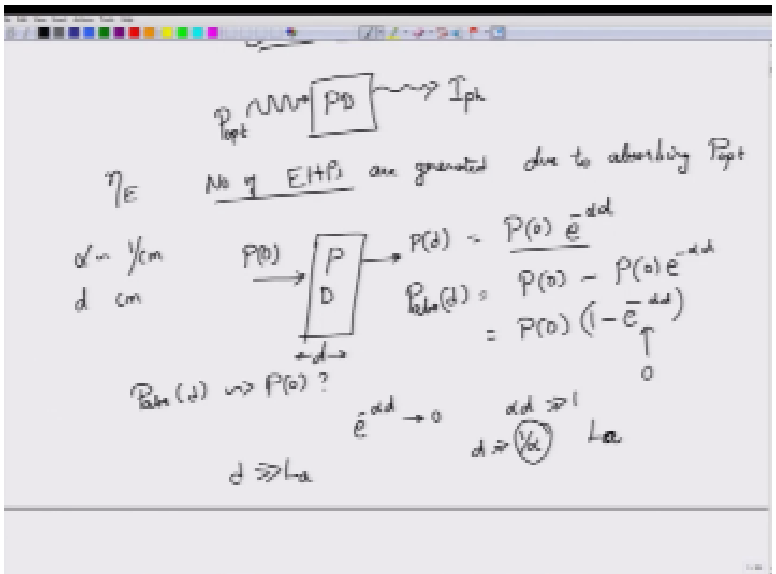

So this is my photo diode which as a thickness of D because one of the thing that I have to first ensure is that if I am generating this electron whole pares due to observing optical power right the optical input power is P opt so if I am observing the optical power I need to know how much I am actually able to observe I mean what determine how much I observe if I am a photo detector and I am bonded with certain photons there has to be certain characteristic that has to be within me in order to observe this photons right it turns out that at the simple level it dependents absorption is dependent on two quantities one is called as the absorption co efficient of the material okay this absorption co efficient is typically a quantity that is measures as one over cm okay.

So if I take a thickness of certain cm d cm then I know that the power observed will be given by I mean will be dependent on α and D okay, I fact you can find out that if at the input you are coming with the certain power optical power p at 0 the power that you get at the output will be you know after absorptions say some power is observed inside and some power of course not observe will come out a residual power.

The residual power will be equal to whatever the input that we have supplied to the photo detector times $e^{-\alpha d}$ this is the attenuation thing that we have seen in our earlier modules for optical communication now if this is the power that is coming out what would be the power observed over the section length D the power observed will be whatever the input power – power that is coming out right.

So this much of the power has been observed inside so this is if you take this p(0) is a common fact so there you get $e^{-\alpha d}$ a quick question to all of you before we go ahead what should I do in order to make the observed power to be almost equal to p(0) a moment is reflection will tell you that I have to make this term go to 0. So when will this $e^{-\alpha d}$ term go to 0 when αd is much, much larger than 1 okay.

Or D is much, much larger than 1/ α we call this 1/ α is the attenuation length okay or the absorption length let us call this as la so what we have to ensure is that my photo detector thickness is much, much large or longer than the absorption length of the material that I am using, now her is an interesting thing we know that if there if I make the detector very long write the thickness of the detector long hen the electron whole pares that are generated must travel towards the end or towards the edge of the region of absorption in order to be collected by the other regions in order to form the current.

Right so my circuit will be connected to the photo detector if the photo detector itself of this length then any electron whole pares that are originating at the junction where the light is being supplied will have to travel all the way here right, so they will have to travel all the way over here or anything that is same maybe originating at the middle electron has to travel here the howl has to travel here in this way.

Whatever the way in which we have connected the circuit but the point is that they have to travel to length worst case scenario edge generate a photo carriers have to travel all the way through the absorption layer right, so if I make this larger yeas I am able to observe my optical power you know in a netter way but long transition time right I start here and then I have travel all the way to the edge the transition time which will be in some sense inversely proportional to the speed of the photo diode will become large the transition time will became large the speed or the response of the photo detector suffers.

So here is our first and main problem I want to absorb as much as power but I cannot do that by simply increasing the thickness of the photo diode, right? So there is actually a trade of between how quickly you want to measure signals versus what would be the quantum efficiency? Okay. In addition to this the second thing that you might be interested is as from the external black box point of view, you have generated,

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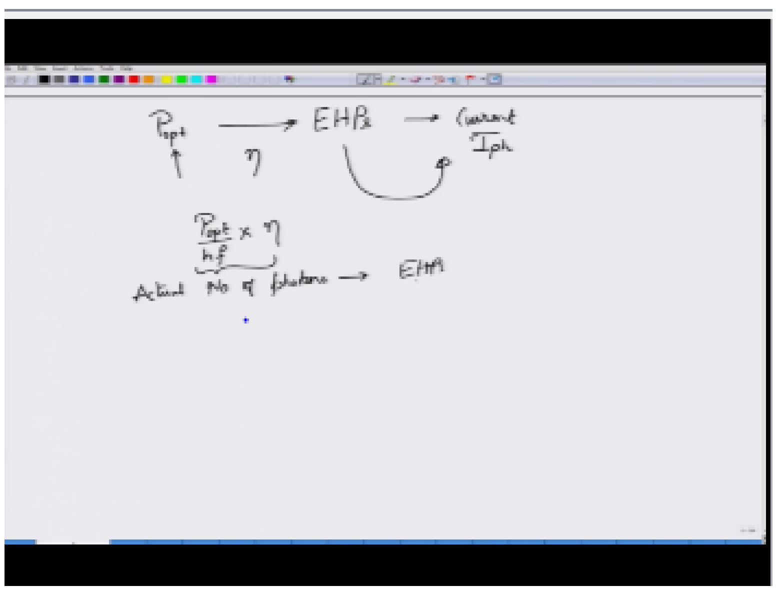

Some electron hole phase, okay which you probably don’t have an accessed right? these electron hole phase have to be converted to electrons in order to form a current, or holes in order to form current, so this have to be collected in the appropriate regions and made to go through the external load resistor that you have connected, okay.

So if you have to do that you have to know how many of these EHP's converted to current, right. Or converted into electrons? Right we know that although an electron hope pair is generated it's the electron which actually kind of physically moves, hole moves virtually right? But weather it's a hole moving virtually or electron moving physically they both will constitute one charge carrier right? So we can actually instead of saying this as current and electrons if I send in some optical power which then gets converted into electron hole pairs which then gets converted into current.

Because electron hole pairs are the photo generated carriers so I should not have distinguish between the two, my point was that electron hole pairs might be generated, but I might not be able to harness all the electron hole pairs that is not all the electron hole pairs that are generated because of the photon absorption will contribute to the final current.

You might ask why? What will happen to those electron hole pairs? I mean they have been generating in the depletion layer so, what is the problem in converting that electron hole pairs in to actual current? Well they are generated but while they are you know drift in towards the region, they might actually recombine, okay sometimes they might be generated and quickly recombine before they have added a chance to go around the circuit.

So because of these losses right and moreover as the election is travelling it might be lost because of the absorption itself, so because of all these factors you don't always are able to convert electron hole pairs into 100% in to a current, okay.

So this quantity again externally one can measure by looking at how much optical power we provide as input versus what is the photo current that is generated? Okay this is effectively what i can measure, so I can take my photo detector bias it, apply an optical power and then look at what is the current right? We were looking at the number of electron hole pairs that can be gainfully converted in to the current right? So we send in a certain optical input power P_{opt} and then you are looking at what would be the current that is generated.

Okay now , what we are interested is to see how much of this electron hole pairs are converted in to current, but what is the number of electron hole pairs that are generated that depend on the efficiency of the photo diode, right? If I send in this many number of photons, because optical power divided By HF will give me the number of photons, right? So this number of photons multiplied by η which is the efficiency.

I am not denoting this by ηe , I assuming that this is just the efficiency which we have defined we don't have to specify it is external, internal for this particular case, so η is the efficiency of the photo diode times P(HF) gives you the number of photons, so this effectively tells you the actual number of photons and these are the numbers of the photons which are generating, the actual number of photons which are generating the electron hole pairs, okay this electron whole pairs, each of them will carry a charge of q, so the amount of carriers that are generated is given by this particular quantity into q. We assume, of course in this particular case, all the electron whole pairs have been able to generate one charge of current.

This number will be slightly smaller than 1, one can decide one more efficiency factor over here but you can also put all those efficiencies into the same η, this were the concept of internal quantum efficiency comes in. So if you don't want to distinguish all that, we can simply say that, η will be the fraction which tells us what would be the optical power to the actual amount of photo carriers that are generated.

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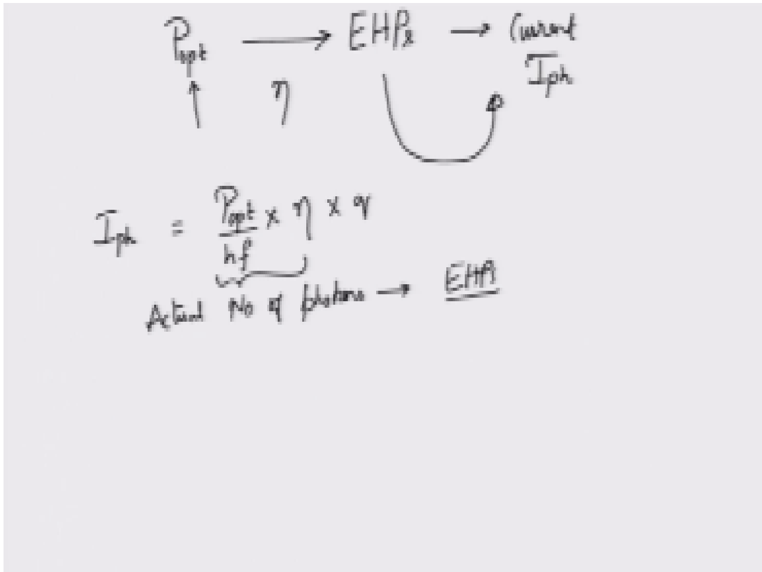

This would be the amount of current that we actually measure on the output circuit; this is the current that we are measuring and this photo current to the optical power is called as the responsivity of the photo diode, so responsivity is something measured, is the quantity measured in ampere per watt being the optical input power, so it is what will be the current in ampere generated to optical input power V applied and this quantity is given by, so you can put this P_{opt} in this equation to the denominator and you see that this is given by q η/hf.

O you can further simplify this expression by calling this q, writing down the value of q which would be about 1.6 $*10^{-19}$ coulomb and h is $6.634*10^{-34}$, I'm just remembering the order of the magnitude over here and then you also have frequency if you express this in term, there are hertz which is the frequency of the optical photon which are used for the optical communication, so these are the tera hertz in the region and hundreds of tera hertz of course.

So this if you put and you can simplify this equation to eliminate all this big order of numbers, let's not do that one here, I will give these simple exercises for you to do that. So to summarize what we have been talking about we want a fast photo diode, which has a low sensitivity, that I can reach, can detect the very small optical powers. O it can detect optical powers which are very small, a low optical power you want a large responsivity again this responsivity is for the PI end detectors.

For an APD detector you have to multiply this one by a certain factor, we will talk about that in the next module, the PI end detectors, the responsivity is measured in ampere per watt and member PI end detectors will only primary electron whole pairs, there is no multiplication electron whole pairs involved there. So you want very large responsivity, which means that there is a large current gain, you also want very high quantum efficiency, so that you can actually observe as many photon as possible.

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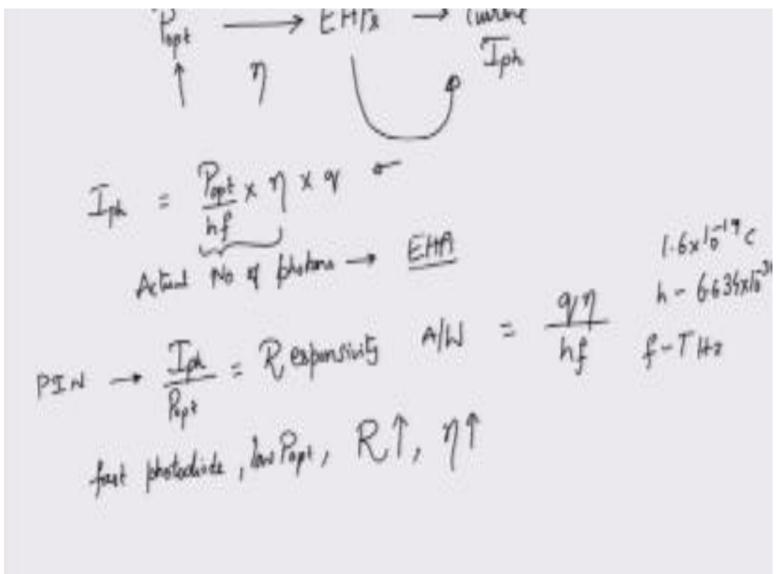

So with this basic idea of a photo diode, we will stop in this module, in the next module we will consider the materials that are used and talk about the two structures of the photo diode. Thank you very much.

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Ministry of Human Resource & Development

Prof. Satyaki Roy

Co-ordinator, NPTEL IIT Kanpur

NPTEL Team

Sanjay Pal

Ashish Singh

Badal Pradhan

Tapobrata Das

Ram Chandra

Dilip Tripathi

Manoj Shrivastava

Padam Shukla

Sanjay Mishra

Shubham Rawat

Shikha Gupta

K. K. Mishra

Aradhana Singh

Sweta

Ashutosh Gairola

Dilip Katiyar

Sharwan

Hari Ram

Bhadra Rao

Puneet Kumar Bajpai

Lalty Dutta

Ajay Kanaujia

Shivendra Kumar Tiwari

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