Fiber - Optic Communication Systems and Techniques
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Lecture – 42
Photodetectors

Welcome to NPTEL MOOC on Fiber Optic Communication Systems and Techniques. In this module, we will look at a very important device. We will learn the fundamental principles of this device and introduce some aspects of noise analysis of this device. We will have to say more about this device when we have already started talking about communication systems, but this device is such an important device in not only communication systems, but you any place where you deal with light and that device is a photo detector.

Photo Detector is usually the contraction of two terms; photon and detector. Photon of course refers to light and detection usually means converting this light energy into electrical energy. It is not necessary that this is the only way to convert or this is the only conversion that is possible, you can also convert light energy to thermal energy and convert thermal energy usually to electrical signal further.

So, you do have different types of energy transduction happening but in the case of communication systems in optical fiber communications or in just general optical communications when we say photo detector, we normally mean that you are converting optical signals into electrical signals. Of course, the reason why you need to do this is very clear your information originally started off in the electrical domain and you after converting this information using the laser as a carrier into the optical domain and propagating it over the fiber and after processing it, you when you come at the input of the receiver, you want to extract the information back into the electrical domain and you do that by putting up what is called as a photo detector.

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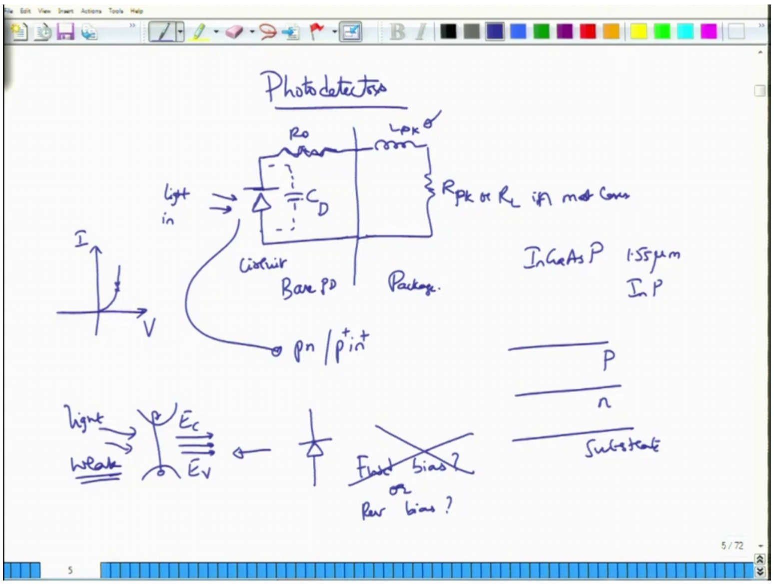

This is a circuit diagram or a circuit representation of a photo detector. This symbol that you see is a p n junction and do not be worried that it is something else. It is actually a pP n junction modified slightly to obtain what is called as a P in junction; pin stands for in the, I in this P and n stands for intrinsic region. So, this is your otherwise you can of course also use a simple P n junction, but these are not that efficient. So, you add an extra layer of I junction. So, technically this should actually be called P plus in plus because the regions surrounding the intrinsic region will be doped very heavily so that the depletion region actually extends far into the other side as well. We will see why that is so.

Now, because this is the p n junction, there is a certain resistance associated with that and there is also a certain capacitance. So, this is how the circuit representation would look like for a bear photo detector as it is called as a bare photo detector and P D is my symbol to denote that this is a photo detector. But when you package it, when you bond it when you know put the wires or leads out of it, we normally also have to deal with some amount of inductance packaged inductance as it is called and there could also be some amount of parasitic capacitance ok.

So, you can include the parasitic capacitance into C D itself and there could also be some packaging resistance in case you wish to have it or usually this is the load resistance assuming that the package resistance which comes off by the soldiering and other things can be kind of neglected, ok. So, this is how you would actually have a complete circuit representation of a photo detector or at least most representation of a photo detector.

Now, I have said that photo detectors are p n junctions. So, clearly I will have a p junction and or rather I will have a p material and then I will have an n material below them will be some sort of a substrate and then you have to launch light into this junction. But before we can do; so, let us ask this question and give you one minute of time to kind of pause the video and see for yourself whether you will be able to answer this question; should I forward bias in the photo detector or should I reverse bias the photo detector? What do you think?

Well if you have passed and thought about it, you would quickly realize that I should not forward bias the photo detector. The reason is very simple. If you go to what is this p n junction, you will again encounter your familiar conduction band and the valence band I am of course, assuming that this is a direct band gap material for example, the most popularly used detector in the 1550 nanometer range are 1.55 micrometer optical communication range is this in gas p photodiode. It can be grown on the same substrate of n p and this gas is a direct band gap material.

So, in gas p is an alloy which has you know a very good efficiency and it can actually work at 1550 nanometer or 1.55 micrometer. So, this I am assuming that this will direct band gap material. It makes our life little simpler the efficiencies are better and things are actually much simpler to understand without the involvement of any phonon which would otherwise be the case for a indirect band gap semiconductor.

So, in this direct band gap semiconductor when I, if I for forward bias the photo detector, then I would actually have created an inversion or essentially I have created you know electrons in the conduction band; a large number of them because I am forward biasing this and then I have this you know empty states in the valence band.

But now, when you apply light there is good chance that these fellows will actually be recombining and even before you apply light because of the forward bias, there is actually a large amount of current that is flowing right. So, if you look at the characteristic of the current to voltage of a photodiode, you would see that just a small amount of bias is sufficient for a large current to flow through and when you launch you know optical signals then instead of optical power being absorbed and then you get something like this, you actually start getting more optical power and because it is depleting and the current would actually reduce.

This is not a very nice way of finding out what is the amount of power that you have sent in because you are trying to deal with this change in the current which may be very hard to do so. Especially, given the fact that most of the light that you incident on the photo detectors happen to be in the communication regime where light power is actually quite weak. So, this is not a very good way of operating this particular device in order to make it into a photo detector what you want is to have a current which we will call as I P H which stands for the photo current to be proportional to the optical power that is incident ok.

So, to the optical power that is incident you must generate certain amount of current. It is interesting that it is the optical power that goes in not the electric field. The reason is very simple power is proportional to intensity, intensity is proportional to the photon energy and it is the energy which is the determining factor to take the electrons from the valence band and to the conduction band. So, it is the energy which is which goes in and energy is of course proportional to power.

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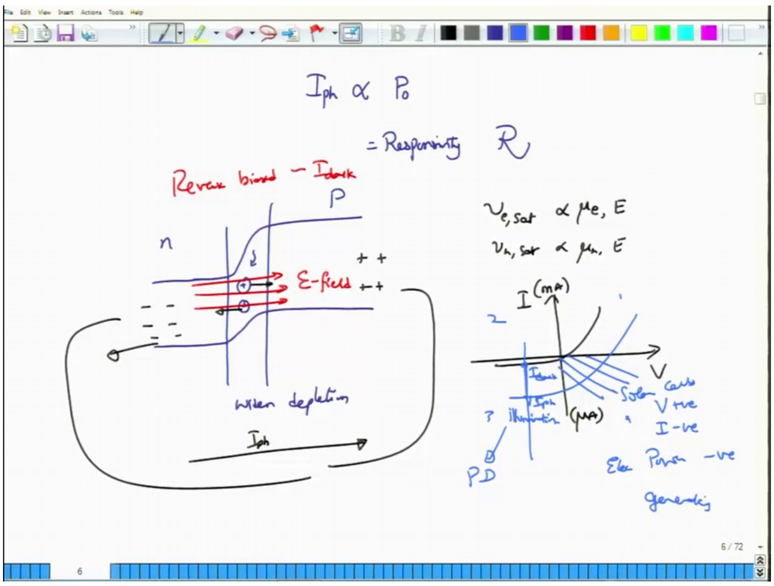

And therefore, the photo current is actually proportional to the optical power ok.

The proportionality constant indeed is called as Responsivity. We will talk about that proportionality constraint which is denoted by this symbol R very shortly, but let us get back to this basic idea. So, I need to have a situation where the current that is flowing in the circuit is the result of only the optical power. Of course, in a practical case you cannot satisfy that one but if you have a P n junction that looks like this by applying reverse bias, what you would do is you would actually increase the band gap and then widen the depletion layer.

So, when you widen the depletion layer and then somehow create an electron and a hole pair here by shining light onto this depletion layer because this is n type region this is P type region, there is an electric field a built in electric field which is very strong and it is strong because you have also increased the depletion layer and increase the bias reverse bias onto the. So, the photo diodes are to be reversed biased so that no current or very little current which is called as the dark current when no illumination has taken place onto the photo detector and this dark current is also sometimes called as the reverse saturation current of a P n junction.

So, only this current flows when there is no illumination or the photo detector is not illuminated. But, once the photo diode is illuminated and you realize that there is already an electric field that goes from or points from electric from the n type material to the P type material, any electron hole pair that is generated in the depletion layer will very quickly attain a large velocity. So, electrons will attain or saturate it is velocity or reach it is saturation velocity which is v e sat which is proportional to the mobility of the electron and the applied electric field, the value of the applied electric field and then similarly you have v h sat which is again proportional to the mobility of the whole and the applied electron with the result that they will quickly be accelerated on to this side.

So, the electrons will move away from the region or away in the opposite direction as the electric field. Poles will move into the same direction where they will combine with the appropriate minority carriers that exist and the diffusion will then further take them away from the regions n and p. Of course, if we keep the region n and P quite small, then most of the electrons and most of the holes which are generated in the depletion layer will quickly come back to the wire and constitute a current in the direction from n to p ok. So, if you look at the v i diagram of a photo diode you will actually see something like this. So, this is how you would see. Please note that the scales here are typically in milli ampere and typically in micro ampere which means that the dark current is quite small it is usually the reverse saturation current is usually in micro amperes or even less than that in very good photo detectors because photo detectors do not want to have lot of dark current and as the reverse pass increases initially without any illumination, it is only the backward or it is only the dark current which is flowing.

But once illumination happens, once you illuminate light you will actually see that the characteristic curve drops down. This increase is because of the illumination. So, which means that for the same bias here, the current has increased from the value which was just the dark current to the photon current or the photo current I p h. This region is also very interesting because in this region you have v to be positive whereas, I to be negative so that the product, V and I which is the power electrical power is actually negative.

Now, negative electrical power means that it is actually generating power and this is the region where the solar cells are actually operated. So, solar cell is operated in this quadrant. I do not know which is. So, this is the fourth quadrant yeah. So, this is first, second, third and fourth whereas, a third quadrant is the quadrant wave the photo detectors are operating. So, this is how you actually have a simple P n junction and the reason why you will actually get photo current but there is not how a device would look.

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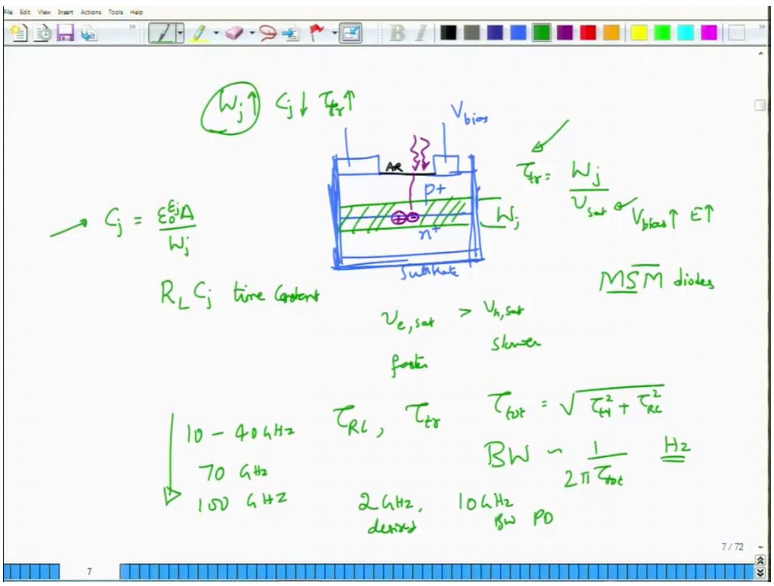

A device would look something like this. So, you have reasonably doped P plus region and then there is an n plus region. There might be some substrate as well and these regions are actually metallized here.

So, there are there is a metal here somewhere sitting down so that you can actually make contact. So, you will have contact regions here so that you can apply the appropriate biased voltage, ok. So, this is how it would be and there would be usually a small layer of anti reflection coating and light would come in from this side. So, you would illuminate from the top so that the lights would actually propagate through and create an electron in the hole pair.

Now, this region would normally be the depletion region and because of heavy doping on both sides, the depletion region is quite wide ok. The width of the depletion region is W or we will call this a W j; j stands for the junction. So, any electron hole pairs which have been generated on an average will pass through W j and they would pass through with a certain transition time or transit time which is dependent on the saturation velocity. It turns out that the saturation velocity of the electrons is larger than the saturation velocity of the holes.

So, holes are most more slower, electrons are faster compared to holes and if it was possible to just have only electrons contributing to the current, then the device speed could be improved and it is in fact possible to actually have those type of photo diodes they are called as metal semiconductor metal, photo diodes where the metal semiconductor and semiconductor metal junctions act like the short key junctions which have only majority carriers. Usually this S is the n type semiconductor and this is also possible they also give you very high photo current for a given optical input and they give reasonably large bandwidth as well.

Now, let us get back to the semiconductor based thing. So, the transit time will be some W j by v sat, but because this has a certain area, the junction had a certain area; they will also be capacitance because of this. The capacitance is of course, given by some epsilon 0 a by W j, we may also want to put in some epsilon j just to indicate the relative permittivity of the junction itself and it is interesting to note that capacitance is inversely proportional to W j and because there is a capacitance and usually the load resistance is much larger than any other resistances in the circuit. So, you have R L C j time constant also into the picture.

So, you your bandwidth is getting limited by two factors; one is tau R C and the other one is tau t r. The overall time delay can be given as the or the overall time delay can be given as a square root of the sum of these two effects. Why do we do the sum of these two effects because we know that, these two are independent processes kind of independent process because the transit time depends on W j, but the actual time is independent of what is the R C time constant. So, to a good approximation these two can be considered to be independent effects and the overall time delay can be written in this way and the bandwidth can be approximately written as 1 by 2 pi t tau and I am expressing of course this one in Hertz in it.

So, typical bandwidths are 10 to 40 gigahertz, high speed photo detectors can reach bandwidths of 70 gigahertz. These days even 100 gigahertz, 250 gigahertz bandwidth have been demonstrated, but please note that these are bare photo detector bandwidths. When you put them into a circuit, the amplifiers circuitry the passive components of the circuit actually pushed down the bandwidth considerably.

So, if you want to get somewhere around two gigahertz bandwidth, you actually start with a photodiode which can give you about 10 gigahertz bandwidth. So, if this is your desired overall bandwidth, then you start with a very high bandwidth photodiode and then after you assemble the circuit this will actually drop. Now, if you have examined this C j capacitance and tau t r you would realize something very interesting; tau t r which is the transit time right. So, this transit time is dependent on the junction width and the saturation velocity. This is something that you cannot do except increasing the v bias so that the electric field actually increases quite large and of course, this electric field also increasing quite large, but if this W j is very wide, then there is no point in increasing this electron because the transit time anyway will increase.

But increasing W j has a good thing right. Increasing W j will need to lower C j of course, increase tau transit time and overall bandwidth will now be affected again. So, there is a certain optimum value of W j that people use in order to balance out the required time constant tau t r and the or the time transit time tau t r and the R C time constant tau R C. So, you do have this combination or the optimization that is going on.

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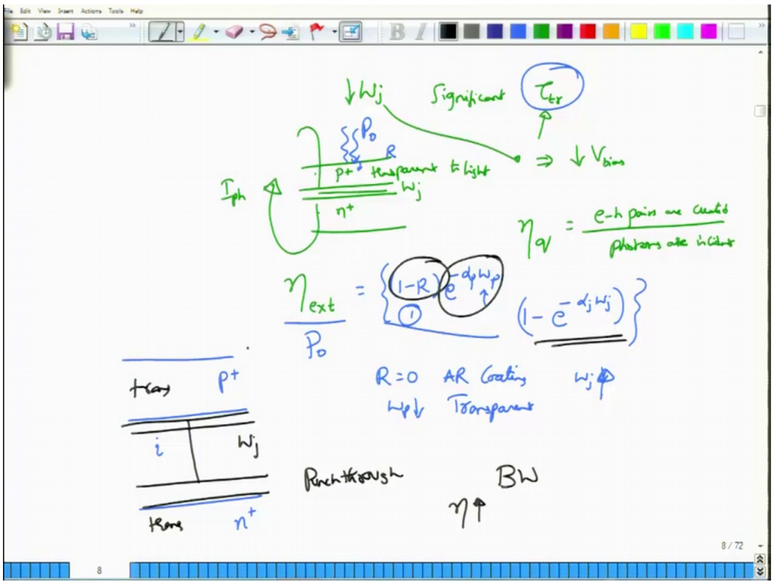

However, for high speed operation it turns out that you have to reduce W j even when you tolerate some amount of increase in the capacitance that is alright because increase decreasing W j has a significant effect in increasing or reducing tau t r which is usually the major limiting factor in the bare photo detector bandwidth. But when you increase W j very short, there is also additional advantage of that; increasing W j means that a lesser value of the bias is required.

So, you do not have to apply say bias voltages of 50, 60 volts. You can apply bias voltages of 5 to 10 volts and that reduces the static power consumption of these devices. So, or rather the voltage requirements of these devices, but when you reduce W j, how do you actually couple light well if you go to try and couple light from the top, there are a couple of things that you need to take care; one is that this P plus region and the n plus region that you have, right; so, these regions that you have to be made transparent to light. If they are not transparent, then photons will be absorbed here. In fact, there will be diffusion currents because of some absorption that goes in the P and the n region and all this absorption would reduce the effective power reaching the depletion layer here and it is their power that reaches the depletion layer which creates the primary electron and holes which determine what is the amount of current that can be generated for a given optical power ok.

And that is characterized by what is called as external quantum efficiency. Quantum efficiency internal or just the quantum efficiency is defined as the efficiency with which the electron hole pairs are created for a given photons that are incident. So, when you send photons, how much of these photon or a single photon if you send, what is the efficiency with which this electron hole pairs are created, but we know that it is not just creation of the electron hole pair that is important, but this electron hole pairs have to traverse the junction to form the, photo current ok.

And the external quantum efficiency actually measures that. When you launch light or when you send light from the top, some portion of the light will actually get reflected away and the remaining portion will be absorbed into the material the first materials. So, you have sayP 0 as the launch power of the optical power; P 0 times 1 minus R where R is the reflection coefficient power reflection coefficient at the front end surface times; P 0 1 minus R times P 0 will be launched into the or will be absorbed by the p plus region.

Where, if you assume that you have a region e power minus alpha p, w P kind of an absorption going on, then the power steadily decreases to then before it reaches a junction itself. But at the junction, if the junction were to be absorptive type of a junction, then e to the power minus alpha g w j would be the absorption, but 1 minus of this one will be the actual thing that is actually transmitted. So, you will you see that there are three factors over here which determine the quantum efficiency. Of course, this is to be divided by P 0. This is the amount of power that is available for the optical signals to generate the equivalent current and when you divide this you know by P 0, the fraction of the power that is reaching into the depletion region which creates the electron hole pairs is what we normally call as the external quantum efficiency or simply the quantum efficiency of the diode.

So, there are clearly three factors; the first factor is 1 minus R and it can be made equal to one by making R equal to 0 which is what an AR coating on antireflection coating at the top of a P n junction would make. You can reduce W P or you can reduce alpha P; so, that this exponential factor will become equal to 1, the way to do this one is to actually use a material which is transparent to this photon that is coming in.

So, you actually use P plus and n plus agents which are actually transparent therefore, there is no loss in photon absorption over here and then, when you increase W j, you are going to increase the possibility of absorbing more, but increasing W j again has lot of problems as we have talked about. It will increase significantly the value of tau t r although decrease in tau R C, but this is an optimization that one needs to perform.

Most photo detectors are actually what is called as p plus and I plus and n plus regions because this is n plus and p plus and the central region is what is called as an intrinsic region, the depletion layer because of p extends far away into this region and n plus region extends far away into this. In fact, sometimes the doping is so heavy that the depletion layer actually exchanged all the way to the other side leading to what is called as punch through ok. So, some of these concepts are reasonably advanced, we do not want to go too detailed into this, but the essential idea is that in intrinsic region that is here which is present will lead to larger values of W j and therefore increase the absorption.

But you have to compensate for this increase in W j by making this p plus region and the n plus region to be being completely transparent so that this factor as well as this factor can be reduced and you are only increasing this factor. Of course, the downside is that you still have to be limited by the amount of tau t r. So, you are actually trading off bandwidth, but increasing this one actually increases the efficiency with which you can absorb photons and therefore, create a larger amount of current photocurrent ok. So, that is what you are going to do.

So, this is the typical v i n structure and this is widely used. There are different structures for especially high speed. So, if you do not care about too much of photo electron being generated photocurrent being generated, then you can reduce W j,

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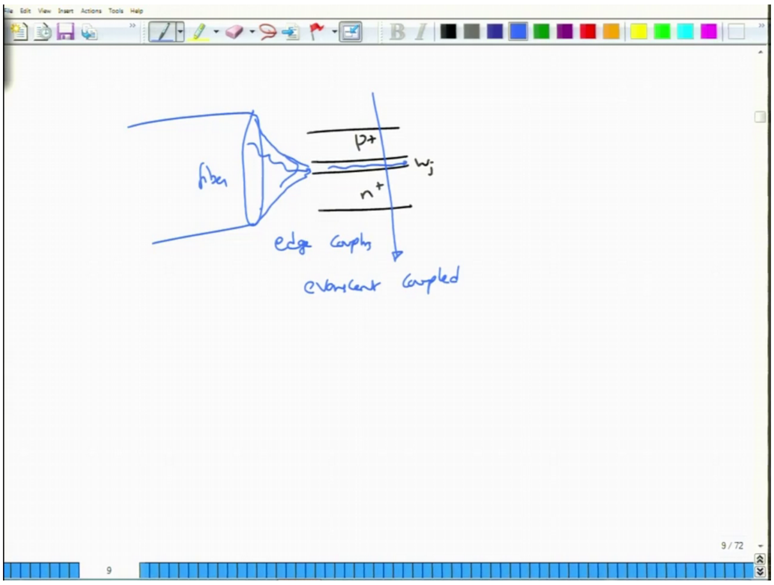

But increase or rather you have this transparent regions p plus and n plus are before, but instead of coupling light from the top, you couple light from the side. So, this is called as edge coupling and you realize that if this is coming off from a fiber, the fiber core area is usually much larger compared to the photo detector side size.

So, what you do is, you can actually put a paper which will take the light you know in a very structured manner and puts it into the junction directly onto this self and here the optical way would propagate along this way while the biasing can be done vertically and there is the problem with small W j does not really arise with this particular structure ok. There are additional structures called as evanescent coupled photo detectors that is also possible to be used here in this context, but those are some advanced photo detector situations that we do not want to cover in this course. We do want to cover the noise statistics of these photo diodes, but that we will be doing it in the next module.

Thank you very much.