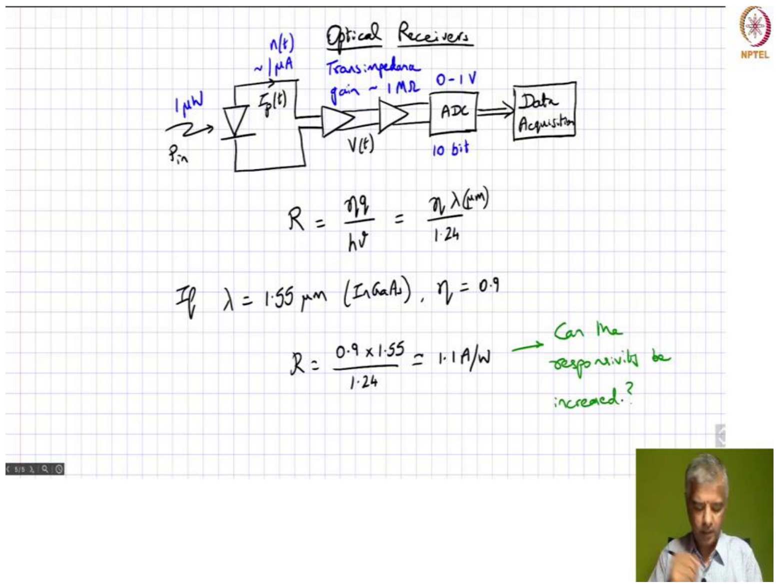
Optical Fiber Sensors
Professor Balaji Srinivasan
Department of Electrical Engineering
Indian Institute of Technology, Madras
Optical Receivers - 2

(Refer Slide Time: 00:15)



Hello friends, in our last lecture we started talking about optical receivers. And in optical receiver, we said the front end is going to be a photo diode, which takes the optical radiation, the incoming optical radiation, and produces a corresponding photo current. And that photo current would need to be converted to voltage. And that is done using a trans impedance amplifier. And with further amplification, it is typically fed into a analogue to digital converter and then that is interfaced with the data acquisition circuit.

So, this is typically the optical receiver that we see, that needs to be designed for any sensor application. We looked at the example of Pin photo diode, we looked at why we need a Pin photo diode, why we need the Pin structure. And then we started looking at some of the characteristics of the Pin photo diode in terms of responsivity, as well as the response time, which can also be quantified in terms of the bandwidth of the overall receiver. So, we stopped at the point where we defined the responsivity are as eta q over h nu.

That is in terms of amp per watt, and since qh and a nu can be written as c over Lambda, since qh and c are all constants, we actually simplified this and said this is eta times lambda over a constant value 1.24 when Lambda, where in Lambda is expressed in terms of micrometres. So, let us see what this means. If we have let us say micro watt of light incident on this. Then what is the corresponding photo current that generated. Well, we can look at the responsivity of the photo diode for that.

Let us say if Lambda is 1.55 microns. 1.55 micron happens to be a very popular telecommunication wavelength. So, let us say for ease of availability of components, let us choose a lambda equal to 1.55 micron. Which material would you use to pick up radiation at 1.55 micron? That would be indium gallium arsenide detector.

Let us say we have one of those detectors. And for indium gallium arsenide, if you design your structure right, meaning you having enough width so that you can pick up most of the light, you can absorb most of the light. That is incident on the photo diode. You can achieve typically values in the order of 0.09, sorry 0.9. If we plug in these values, then we find that R is now 0.9 multiplied by 1.55 divided by 1.24.

And if you quickly do the math that would correspond to about 1.1 amp per watt. So, that is the kind of number that you get for the responsivity. So, what that means is if I have one micro watt of power that is falling on the photo diode, that is actually incident on the photo diode, then the photo diode would say generate about 1.1 micro amp of current. So, I will just say approximately 1 micro amp of current.

And this needs to be converted to a voltage and then maybe amplified in terms of its amplitude. And then finally you are amplifying the signal so that it fills the ADC. So, if you take a 10 bit ADC you have 1024 levels in that. And if the ADC has swing of 0 to 1 volt, let us say if you want to use all the bits of the ADC. You need to fill the ADC, which means that you need to boost up the signal which is say, 1 micro amp.

That is a maximum that is falling on the photo diode I mean it is the maximum photo current that is generated you need to convert that to 1 volt. So, what is the trans impedance gain you need? Well, you can calculate the trans impedance gain here. Gain is going to be 1 volt divided by 1 micro amp. So, that will be 1 mega ohm. So, 1 mega ohm is the trans impedance gain that you need.

So, yes, you say, 1 mega ohm what is a problem with that? Well, we will see what might be a problem with this a little later on. But just give you a hint, these amplifiers are typically op amp based amplifiers and these amplifiers would have a certain bandwidth gain product or a gain bandwidth product. So, what that means is if, for example, you take an op amp 741, it has a gain bandwidth product in the order of one meg, what that means is you can get one meg trans impedance gain using this op amp.

But that will come for only 1 hertz of bandwidth. On the other hand, if you want to have at least 1 kilohertz of bandwidth, then you are limited to a gain of only 1 kilo ohm. So, issues like that can actually put a limitation on this. And these are issues that we will come back and look at little more detail slightly later.

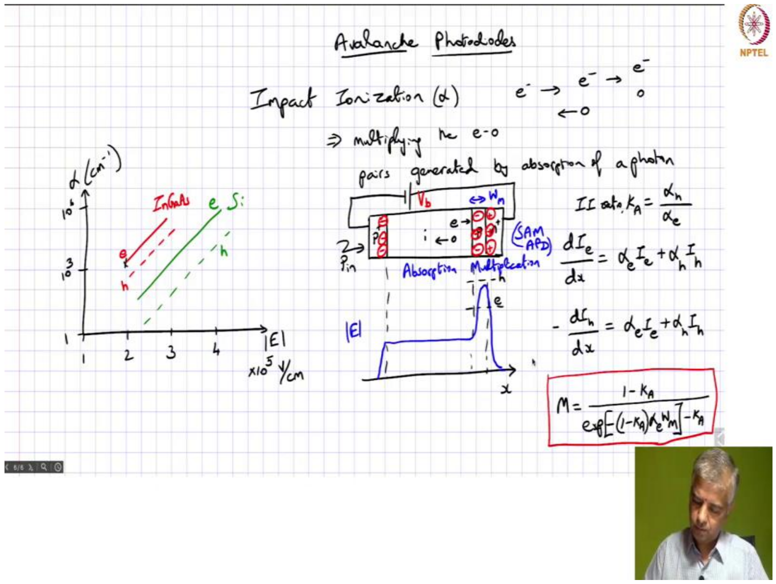
But the other aspect is any noise that you have in your photo diode that you generate from your photo diode, maybe because of incoming light itself is noisy. Or maybe there are some processes within the photo diode that generate that noise. Any noise that you generate there is actually going to be, let us call it, n of t write. So, this tends to be like an additive noise on the signal that you are trying to capture here.

That noise is going to be also amplified by this 1 meg ohm. So, this is actually an important aspect to note, the signal to noise ratio in your receiver is going to be highest at the front end. It cannot improve as you go further down the receiver. There is a misconception that, oh, I can put amplifiers and I can improve the signal to noise ratio. No, that is not what is happening.

Whenever you put an amplifier, you are boosting up the signal, but you are also boosting up the noise by the same level. So, the signal to noise ratio can only degrade as it goes through all these amplifiers because the amplifiers also add extra noise. So, it will further degrade the signal to noise ratio that you have. So, it is very, very important that you need to have highest high signal to noise ratio as possible right at the front end itself.

And the related question is. Can the responsivity be increased somehow? Is that possible at all? Well, it turns out that is possible and that is actually through what we call as avalanche photo diode.

(Refer Slide Time: 10:05)



So, let us actually look at what are avalanche photo diodes mean. So, we did look at this concept a little earlier that as you increase your electric field. As you increase your electric field inside your semiconductor photo diode, you have especially at the junctions you have, you are under the influence of drift mechanism and under that influence, your velocity of the carriers can be increased.

So, suppose you are going to very high fields levels, let us say fields levels in the order of 10 power **five** volt per centimetre. If you have if you have that sort of field levels, that is very close to the breakdown strength of the material itself. Under those intense fields, the carriers are subjected to so much high momentum.

They carry so much momentum that they could impede, they could actually collide with atoms in the overall matrix. And you could essentially when it collides with atoms with such high momentum it ends up generating, it basically knocks off electrons from the valance orbital. So, in this case, you can look at it as electrons going from the valance band to the conduction band. Once it gets knocked off from the atom it goes into the conduction band.

So, whenever that happens, of course, it also leaves behind a whole. So, you generate an electron, a secondary electron hole pair due to this primary electron that is traveling with very high velocity. So, this process is what we call as impact ionization.

And impact ionization essentially means that you can start with one electron, and that actually generates an electron hole pair. And then it still has, because the momentum has transferred to this new electron now that electron can still have enough momentum that generates secondary electron hole pairs and so on. And similarly, if the hole also is moving with a fairly high velocity, the hole can go and generate secondary electron hole pair as well.

So, that could also participate in this impact ionisation. So, through the process of impact ionisation you are essentially multiplying the electron hole pairs generated by where is it all triggered, it is generated by absorption of a photon. So, you start with absorption of a photon that generates an electron hole pair. But under intense electric fields that can generate secondary and further electron hole pair. So, there could be a multiplication happening and that multiplication process can lead to an avalanche.

And that is why such photo diodes are called avalanche photo diodes. So, let us actually look into this a little more detail. Let us say the impact ionization can be expressed in terms of alpha. So, I can draw a graph where alpha, which is typically expressed in terms of inverse centimetres, can be plotted as a function of the magnitude of the electric field. And I would say, let us look at this magnitude in terms 10 power 5 volt per centimetre.

So, 1, 2, 3, 4 and so on. And then the Y axis, this could be 1, 10 power 3, 10 power 6 even it is a huge number. So, we can get multiplicative gains in the order of 10 power 6 even with this impact ionization process. So, how does this look say for silicon or for indium Gallium arsenide? Let us say start with Indium Gallium arsenide would have something like this. You can get 10 power 3 gain. That is 10 power 3 per inverse centimetre gain. And this is for let us say electrons, the impact ionization coefficient for electrons.

Whereas for holes. The impact ionization is slightly less the coefficient is slightly lesser. So, that is typical numbers for Indium Gallium arsenide. So, this is Indium Gallium arsenide. And the other hand, if you look at silicon, silicon actually has even lower impact ionization coefficient. So, that is something like this, but significantly, when we look at the impact ionization coefficient for holes in silicon.

So, this is for electron and this is four holes that is even lower, much lower compared to the impact ionization for electrons. So, what is the corollary of this? So, what does this all mean? To understand that we need to actually or how do you, first of all, trigger this impact ionization mechanism? What are the typical type of structures that are used for this? Well, you would still use a Pin structure. So, I start with what we drew before.

I would still have a relatively small p region. So, let us say heavily doped p plus, and then you have this i region and then you go to this region and here you have like before we have a n region, let us just call that it is highly doped n region. And so we call it n plus. Now, what if we can add one more layer over here and a p type layer?

So, what happens in this sort of case? Well, of course, we know that because of the charge transfer that happens at these interfaces. Let me just represent this in a different colour. I am going to from the p type. I am going to leave behind some negative charges over here. Similarly, on this side also I am going to leave some negative charges. And over here, I am going to leave some positive charges. So, it is fixed ions over there.

So, because of this, when you look at the electric field across the structure. So, let me just draw this out here. If I am plotting the electric field across the structure, electric field is going to be something like this, it is going to increase over here. This is the magnitude of the electric field. And then it is going to remain almost constant over here. And over here, there is actually a sudden change in the charged density.

So, accordingly there is going to be an increase in the electric field and then there is going to be a decrease. And then it goes back to 0 beyond this. So, this is different, this is different in this structure compared to the previous structure of the Pin photo diode, where the electric field was constant across this entire region, entire i region. But what we have done is we have actually added one more layer over here.

Where you have a much higher electric field, so when you apply an external bias to this, so when I connect this to just a reverse bias like we did before. If I connect it to a reverse bias and I increase this bias voltage if i increase the reverse bias, then my this peak is going to keep on increasing.

And you can get to a point where the field levels are somewhere like this. And so that may happen somewhere over here. So, you may achieve that threshold at this sort of level and any higher voltage than that corresponds to a higher field, you are going to have even higher impact ionization coefficient. So, this is what happens, so this threshold actually, if you go beyond that, you start having a lot of impact ionization events happening and then because of that you will have a large multiplicative gain happening.

So, essentially, like before, what we are doing is we have this incoming light pn and that is getting absorbed all along the i region. And because of that, you generate an electron hole pair. The electron moves this way, the hole moves this way. Then the electron is actually as it is going through this medium it is getting accelerated and it has so much momentum that it generates this. It basically undergoes this or triggers this impact ionization.

And then beyond that it generates much many more electron hole pairs. Which are once again, because of the large field here, they are swept across this region and then it generates a photo current of the external circuit. So, if we were to quantify this, you would want to quantify this in terms of the current that is generated in terms of the photo current that is generated.

And that can actually be written as like this dIe over dx. Let us say this is x this is the special parameter, dIe over dx is given by alpha e, which corresponds to the impact ionization coefficient for electrons times Ie. Because the current due to impact ionization of electrons. That is, that is what we are denoting as Ie it goes as this rate plus you could also have electrons generated because of impact ionization of holes. So, you could also have Alpha h Ih. So, so that is also possible.

Now, you would want to say that if I can get both electrons as well as holes generating my impact ionization. Then I can get larger gain. So, basically in this picture, what it says is that if this is the threshold for electrons, my hole threshold is somewhere over here. Because the holes take a larger electric field to generate that sort of multiplicative gain. So, that gets triggered over there.

So, you would say just keep increasing it. And then have holes also participate like this hole can now cost impact ionization and they can also generate electrons, secondary electron hole pairs. Well, that that would be a good thought, except for the fact that this impact ionization process is a, it is a random process. You cannot say that one electron is going to generate 10 electron hole pairs exactly. It could be 8 at some time. It could be 12 at some time. It could be 15 at some time, or it could be even 5 some of the time and so on.

So, it is actually a random process. So, we know that any random process can be characterised by a certain variance and that variance is essentially noise in our process. So, just the impact ionization process itself is expected to have a certain variance and expected to have a certain, generate a certain noise. So, you cannot actually have both electrons as well as holes participating because if the holes also are generating their own random process, then the corresponding generated current is going to be that much more noisy.

So, there comes a point beyond which the avalanche process actually defeats the purpose. You up to a certain point, you have this multiplicative gain improving the responsivity, but then beyond a certain point, it also introduces so much noise that the signal to noise ratio is not increasing.

So, that is actually a key point to note. So, you have what is called an optimum bias voltage as far as operating avalanche photo diodes is concern. The optimum bias voltage is determined by how far is the threshold for the holes from the threshold for the electron. So, from that perspective you can say that in silicon the difference between electrons and holes are so much higher, the impact ionization coefficient that the threshold for holes is at a much higher level.

So, you are able to keep increasing your bias voltage and keep getting higher and higher multiplicative gain for a silicon photo diode without incurring extra noise up to a certain voltage. So, that voltage is much higher for silicon compared to indium gallium arsenide. So, you are able to effectively get much higher optimum gain values for silicon compared to indium gallium arsenide. That is the take way point.

But in general, this is what we call as, this structure is what we call as separate absorption, because this is where the absorption is happening primarily, and this region is where the multiplication is happening. So, it is a separate absorption multiplication photo diode. So, that structure is called as SAM APD.

So, this particular design is called a SAM APD and that is one of the more popular APD's that you find out there. Of course, like I said, this is not only generating current due to this electrons, it is also generating a current due to holes. And that is actually going in the opposite direction that is why there is this minus sign here. But that is also given by Alpha e Ie plus alpha h Ih.

Now, we can solve these rate equations and with certain boundary conditions, boundary conditions are essentially saying that the avalanche process is triggered by this electron coming from this region. And there are no holes coming from this region. The hole current is 0 when you start from with some of those sort of boundary conditions and the charged neutrality, which says that whenever a electron is generated there is also volt is generated.

So, the electron current and the hole current is the sum of both of those as a constant. And that is uniform across the entire structure. So, you can do all of this, and then you can actually represent, you can actually get a expression for this, you can solve this equations and you can get an expression for the multiplicative gain. That gain value happens to be, you can call that as M. M is actually expressed in terms of the impact ionization coefficients, and it is convenient to represent this ratio of this impact ionization coefficients.

Let us say this is the. So, this is the II ratio impact ionisation ratio KA which is given by impact ionization coefficient for holes divided by impact ionization coefficient for electrons. So, just a quick word about the value of KA. The value of KA can be anything from 0 to infinity. So, it depends on the relative values of the impact ionization for holes and electrons. So, which is a good value to get optimum gain. Well, you can say that if KA equals to 1, in which case, you know, impact ionization coefficient for holes is the same as that for electrons.

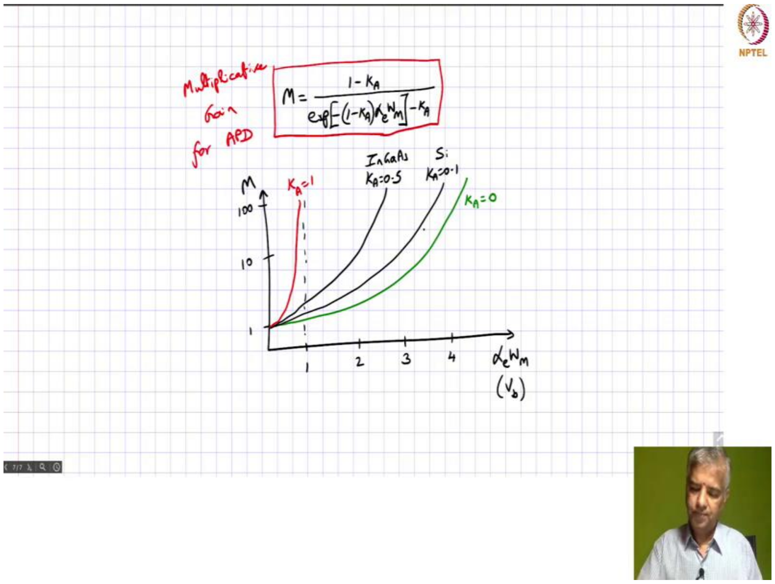
If that is the case, then both of them have the same threshold and both of them are participating in this process, in the avalanche process, and they generate a lot of noise. So, overall you will not going to get a very good gain from this process without incurring significant noise. So, it becomes counterproductive. On the other hand, if K is closer to 0, let us say alpha e is far far greater than Alpha h. Let us say for example, in silicon, that is what we see alpha e is far far greater than its order of magnitude, greater than that for holes.

If that is the case, then KA is a very small value. And that means there is a large gap between these two thresholds. So, only one type of charge carrier in this case electron is generating all the impact ionization events. So, that is actually a preferable condition and then that would also result in a higher multiplicative gain. So, let us actually quantify that. So, like I said, if you work out these rate equations with the boundary conditions and all you come up with an expression like this.

Which is given by M equal to 1 minus KA divided by exponential of minus 1 minus KA multiplied by Alpha e Wm. So, I have not defined Wm yet. Wm corresponds to the width of this multiplication region. So, this is my Wm. So, this minus KA. So, that is actually the expression for the multiplicative gain, which depends on KA, which is actually a constant for any given material. So, you can pick the material based on its value of KA and then what are the other parameters you have alpha e.

Which you can control. How do you control Alpha e? Well, if you go back and look at this graph, it is controlled by controlling the electric field. And how do you control the electric field? By controlling the bias voltage that you have here the v bias. So, by controlling v bias, you can actually control Alpha e. And Wm is actually a parameter that you design up front. And it is a relatively small value, smaller than the width of the intrinsic region typically. So, that is actually the expression for M. So, let us actually look into this in a little more detail. And to do that, let me actually try to copy this. And let me just go to a fresh page.

(Refer Slide Time: 35:27)



So, what we are looking at is this expression for the gain, this is actually the multiplicative gain for an APD. So, let us just plot this and see what it means.

So, on the y axis, I am looking at M which starts from 1 and I can go to 10, 100 and so on. Whereas in the y axis I have Alpha e Wm which is actually representative of the V bias, because that is what you are changing to change Alpha e Wm and, so, that is 1, 2, 3, 4 and so on. So, if you have something like this, let us actually look at two extreme conditions. One is where KA equals to 0. If KA equals to 0, then this becomes 0. This becomes 0. Then this also becomes 0.

So, then you have exponential of Alpha e Wm. So, that would correspond to something like this. So, this is actually KA equal to 0. And then the other condition is when KA equals to 1, if KA equals to 1, then this becomes 1. And then if you substitute here, this is also 1. So, that is 0. So the whole thing is 1. So, 1 minus 1 that is denominator is going to be 0. So, that is (())(37:57). So, ((37:59)) rule and then you work it out. What you will find is for that condition, it will tend to be asymptotic.

It will work out to be 1 over 1 minus Alpha e Wm. And so that will be asymptotic with respect to, with respect to this value of 1. So, it be something like this. So, this is for KA equal to 1 and for other values of KA, for example, silicon is KA is 0.1. So, then it will look something like this. 0.1 for silicon and KA is 0.5 for indium gallium arsenide. So, so this is KA equal to 0.25 indium gallium arsenide.

So, you look at this picture and you say KA equal to 1 seems to be a very good condition because of the fact that even for very small values of Alpha e or very small values of bias voltage, you can get a very high gain. But that is only one part of the picture. We have not actually started talking about noise that is generated from avalanche photo diode from a perspective of noise.

You will find that this is actually the most noisy condition, whereas KA equal to 0. It although it says that it is a very slowly evolving exponential. Nevertheless, you would find that for this condition, you will have, you will be able to go to much higher levels of gain. So, we will look at some of these final features soon in the next lecture.