Optical Fiber Sensors
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Lecture: 9
Optical Receiver Design

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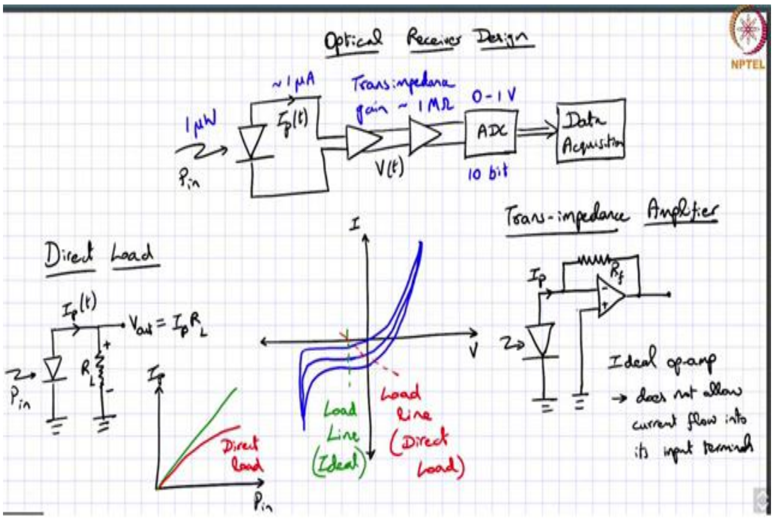

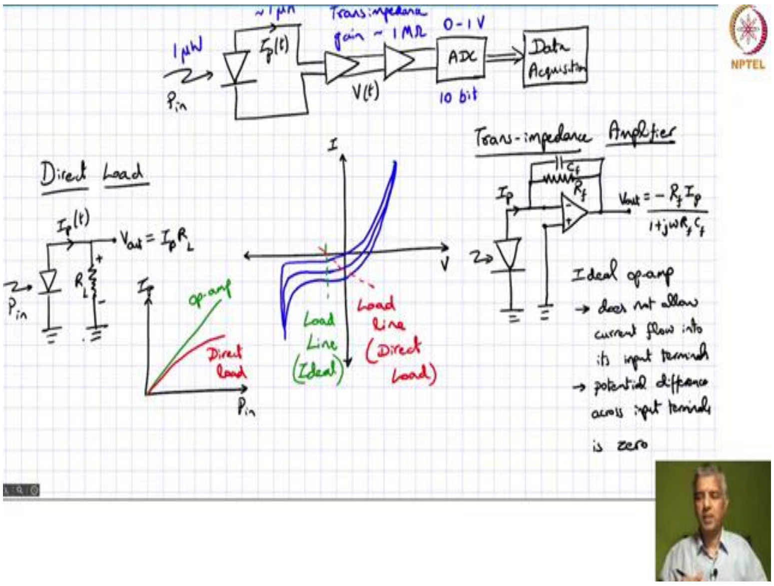

So far, we have been talking about these photodiodes, which is actually the front end of the optical receiver. And we understand now, that you have light incident on this photodiode and the photodiode generates a certain photocurrent it could be a PIN or APD photodiode, but it generates of certain photocurrent.

Now, we discussed before in terms of the overall optical receiver design, we need to convert that photocurrent into corresponding change in voltage. So, what are the kind of circuits that you would want to consider for something like that? That is what we want to look at next.

So, one simple configuration is what you would call as a, I will use a different color, direct load configuration. And in a direct load configuration, what we have is this photodiode, which is going to generate the photocurrent upon certain light that is incident on it. This could be grounded or it could be with some bias as well. But this photocurrent, that is generated at I P, which is actually a function of T.

Now, that is going to that external circuit, and then you typically have, in this configuration, a resistor, of value, let us say R L, and then you are looking at the output between, the potential difference between this point and ground. So that should correspond to I P times R L. So, that is what you get at the output.

Now, what really is happening over here? Well, the photocurrent actually flows through this resistor. And so, there is actually a potential difference, which is what you are trying to pick out over here. But in doing so, one thing that happens is this potential that develops here is going to act against the potential difference across the diode or in other words, if you, let us say you have a certain bias over here, certain reverse bias.

Now, this potential difference is going to work against that reverse bias. And that may end up, limiting the current, the best way to look at what is happening there is by looking at the I V characteristics of the photodiode, especially under this loaded condition. So, let us go back and I am sure you have seen this before, I V characteristics of any photodiode, any diode for that matter. So, this is I and this is V, and I use a different color here. So, the reverse bias case, it goes to certain, in a certain point it goes to break down, but it goes as an exponential under forward bias.

So, the question is what happens if you have light incident on it? Without any light incident on it, if you change the voltage across the diode, this is what you get to see as far as the current is concerned. But what if there is light that incident on it? If there is light incident on it, then what we will find is that correspondingly there will be a change in the photocurrent.

Basically, the reverse current, that you are getting off the photodiode. And so, you would have an increase like this and so on. So, you will have a corresponding increase like this. And this is actually as a function of increasing intensity or the power that is falling on the incident on the photodiode.

Now, let me just see if we can take this out because I want to write something else there. Ideally, what you want across this is something like this, you want what is called load line. In the ideal case should be something like this as you increase the intensity you should be able to get a corresponding increase in the photocurrent. So, in other words, if we were to look at this photocurrent as a function of PIN, the ideal case it should be like this, it should increase with the incoming optical power, but what is happening in this direct load?

Now, as we talked about because of the photocurrent that is follow, that is going through this resistor, you have a potential difference here and that potential is acting against the potential that the diode is experiencing, which could be a reverse potential. So, effectively the load line now is not the same as what we have over here, instead the load line goes something like this.

And maybe just to reduce the confusion, I should remove this part here and say this, this is actually the load line for direct load configuration, meaning as this current goes in, and then it is setting up a potential here that is effectively reducing the potential. And in that process, it is also limiting the current.

So, the current should be over here, but because of this potential that is developed, the current is actually lower. So, it is actually limiting the current. So, because of this load line, now, what we are saying is your current is going to be limited. So, this is what happens in a direct load configuration.

So, direct load configurations are not very good. If you want to actually extract the most amount of current from your photodiode corresponding to the amount of light that is incident on that photodiode. So, what is the way out? What can we do to get around it? Well, you have a configuration based on an operational amplifier. And this is actually a configuration that is called a Trans-impedance amplifier. So, what is the configuration for a Trans-impedance amplifier?

Well, we have the same, configuration here as far as the photodiodes concern, maybe it is grounded or maybe it is biased. But then there is a photocurrent that is generated. Now, this is actually connected to an Op-Amp. With the other input or the Op-Amp may be at ground. So, you connect to the negative of the Op-Amp, because, what we will see further down is actually this is corresponding to a feedback circuit over here. So, if you connected to the positive there is a possibility of this circuit becoming unstable and then it can basically become an oscillator with positive feedback.

So, we typically prefer the negative feedback configuration for something like this. And if you have in this case, I P that is generated because of light that is instant on this photodiode the properties of the Op-Amp actually comes into the picture. So, what are the properties of the Op-Amp?

Well, for an ideal Op-Amp, one property is that it does not allow any current to flow into the terminals. So, an ideal Op-Amp does not allow current flow into its input terminals. So, that is one property and by that what we are saying is, the current cannot flow here. So, it has to flow in the feedback circuit, where you might have a certain resistor R F.

The other property of an ideal Op-Amp is that when you look at the potential difference between the two input terminals, the potential difference has to be 0, potential difference see, if I can make myself some room, potential difference across input terminals is 0. So, what does that mean? Well, you do because of the current flow over here the current is actually if it cannot go here, it goes through the feedback circuit. So, there is a potential that is generated over here. Now, this is a virtual ground. So, there is a potential difference between these two.

So, what does the Op-Amp do? Well, the Op-Amp essentially sources a current from its output and, and essentially tries to negate that potential, with the effect, that when you look at the output voltage across the Op-Amp, across this point, that will correspond to minus of R F multiplied by I P. It is minus because it is actually connected to the negative feedback terminal.

So, you get an output, correspond to minus R F multiplied by I P. So, how is this different from this case, from the direct load case? Well, in direct load we say, we see that the load line is actually slanted which means that it limits the current that you can extract out of it.

Whereas, as far as this trans-impedance amplifier is concerned, there is no such restriction. I will say there is no such restriction, but I would also say that eventually there is a restriction because there is only so much current that this Op-Amp can provide. To negate this or to nullify the potential difference at the inputs.

And so, it cannot I mean, the Op-Amp is rated for a certain output current. So, it cannot provide any more current than that. But that is a non-ideal condition. So, until that happens, you are able to extract the photocurrent. So that typically happens for an Op-Amp in the order of 10s of milliamps. So, you are typically fine with that.

So, effectively, what we are saying is, the load line for a trans-impedance amplifier is going to be closer to this ideal condition. So, an Op-Amp would essentially behave like this, in terms of the current that is extracted for the amount of power that is incident on the photodiode.

Like I said, it will probably saturate over here because of the limitation in terms of the current that the Op-Amp can supply. That is a secondary thing. Overall, this is actually a much better configuration, a trans-impedance amplifier, if we are interested in extracting as much photocurrent as possible from your, from your photodiode.

And, that is one of the more common configurations that is used. In reality, this is all that we have talked about is actually the DC characteristics, when you are talking about AC characteristics, you are interested in the frequency response of your circuit, you have to also consider certain feedback capacitance also here, CF, which could be some spurious, some parasitic capacitance that you incur in your board or this resistor value itself can exhibit certain capacitance.

So, you have essentially an RC circuit in the feedback, because of that, when you look at the overall response of this, the response would correspond to 1 plus J omega R F C F the frequency response in as far as the AC condition is concerned, will be given by this.

So, what that tells you is that this amplifier is going to be providing this gain only up to a certain frequency, a certain frequency wherein this frequency comes in this omega, omega is 2 pi F. If F is much greater than 1 over R F C F, sorry, F is much lesser than 1 over R F C F. Then this entire component will be very small, so it may be neglected.

So, at low frequencies, it may be neglected. But as you increase your frequency, as you approach that 1 over R F C F value, you are going to have essentially the amplification getting reduced. So, the frequency response is going to be poorer as you go to higher frequencies.

So, there is a limitation in terms of the bandwidth that you can achieve based on this configuration. So, that is one of the downsides, as far as a trans-impedance amplifier is concerned. We did not talk about it explicitly. But even if you go back to this, you would say that this photodiode has got a certain capacitance.

So that capacitance in parallel with this RL, that also provides you sort of bandwidth constraint as far as the response is concerned. So, that is not anything different, as far as compared to this, what is happening with this trans-impedance amplifier case. However, there is something else that is happening in a trans-impedance amplifier, which further sort of constricts the bandwidth. So, what is that? So, let us look at this in a little more detail.

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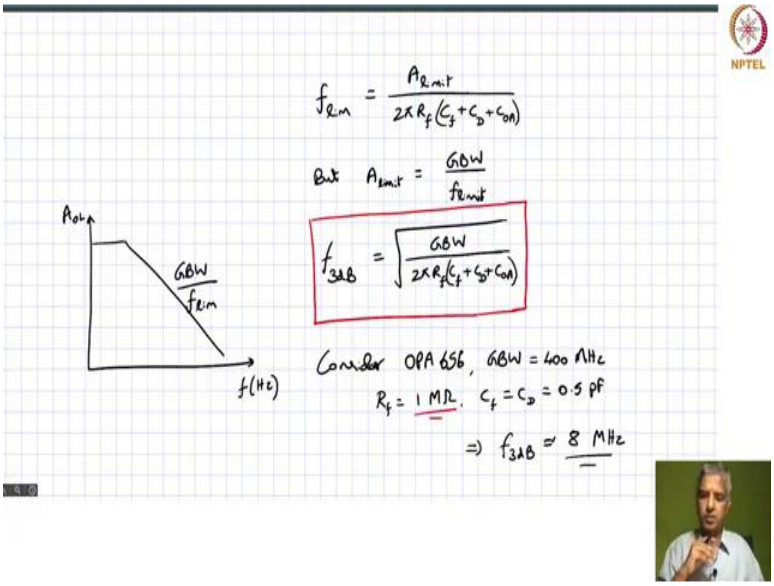


$$f_{lim} = \frac{A_{limit}}{2\pi R_f (C_f + C_D + C_{OA})}$$

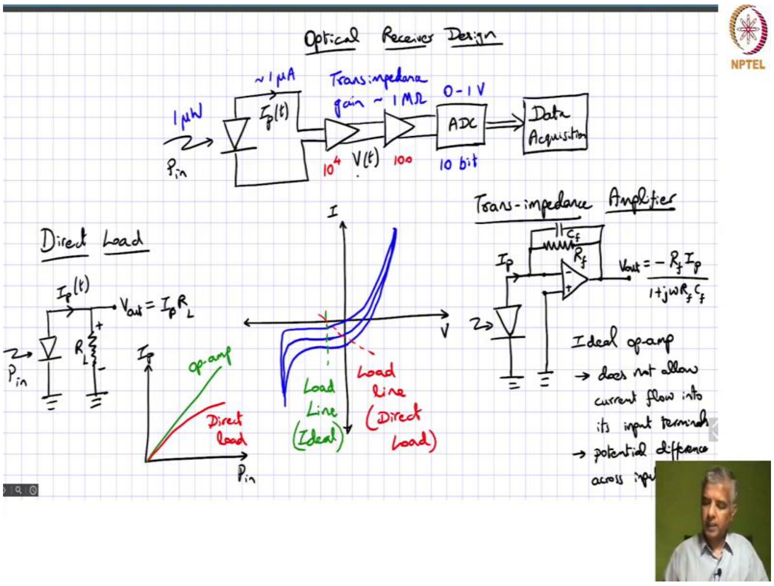
But $A_{limit} = \frac{GBW}{f_{limit}}$

$$\boxed{f_{3dB} = \sqrt{\frac{GBW}{2\pi R_f (C_f + C_D + C_{OA})}}}$$

Consider OPA 656, GBW = 400 MHz

$R_f = \underline{1\ M\Omega}$, $C_f = C_D = 0.5\ pF$

$\Rightarrow f_{3dB} \simeq \underline{8\ MHz}$



Optical Receiver Design

Direct Load

$V_{out} = I_p R_L$

Trans-impedance Amplifier

$$V_{out} = \frac{-R_f I_p}{1 + j\omega R_f C_f}$$

Ideal op-amp
→ does not allow current flow into its input terminals
→ potential difference across inpu

Now, when we look at the frequency response of this Op-Amp itself. So, what is called the open-loop response of the, open-loop gain of the Op-Amp as a function of frequency that typically, it is like this, it is relatively flat at low frequencies, but then it starts going down as you go to higher frequencies because there is a certain gain-bandwidth product, which is actually limiting the gain that you can achieve from the Op-Amp, which is essentially saying that if you go to higher and higher frequencies, the gain that you can extract from the Op-Amp is going to be lower.

And this is going to be given by what is called this gain bandwidth divided by whatever is the limiting frequency that you want to apply over here. So, the limiting frequency that we are typically interested in is the 3 dB frequency, where the response of the receiver goes down by a factor of 2, that is called the 3 dB frequency.

So, F limit could be the 3 dB frequency, but for any of these Op-Amps, if you are looking at the expression for the F limit based on what we looked at here, based on the frequency response over here, you can write the F limit as you have this A limit the open-loop gain at that particular frequency divided by 2 pi R F C F, but you could also have other terms, you could have terms corresponding to the diode itself.

If you just go back and look at this, this capacitance across the photodiode that is actually in parallel to C F. And also, there is a capacitance corresponding to the Op-Amp the input of the Op-Amp. So, that is also parallel to CF. So, you can have multiple terms over here. So, basically say, C F plus C D plus C O A.

And you could maybe even add other parasitic capacitance because of the traces in your PCB, in your printed circuit board. So, that is actually the expression for the F element, but what we are interested in is actually, but we also know that your are A limit is given by gain bandwidth divided by F limit.

And you can choose that F limit to be corresponding to your 3 dB frequency in which case what we are saying is, this is gain bandwidth divided by F, F can be taken over there. So, that becomes F square is equal to gain bandwidth divided by this value or F 3 dB can be written as square root of gain bandwidth of the Op-Amp divided by 2 pi R F CF plus C D plus C Op-Amp and so on. So, effectively your 3 dB bandwidth is going to be limited by the gain bandwidth of your Op-Amp. And of course, you also have a limitation with respect to the R F and C F C D. So, you try to keep these capacitance values, as small as possible.

And for example, you pick an Op-Amp, whose input capacitance is a much lower value compared to these two, so that you can neglect this and you can consider these. And you can keep the feedback capacitance, that parasitic capacitance, and all that to about 0.5 Picofarad. Let us say, you can actually reduce the diode capacitance by having a larger bias across the diode.

So, as you increase your reverse bias voltage, you would typically find that this capacitance or the ability to store charges in within that diode actually reduces as you go to larger reverse bias. So, the capacitance value could be reduced because of that. So, let us actually look at some realistic values. For these, come all these different things.

Now, consider, say a popular Op-Amp OPA 656, which has gained bandwidth product of roughly, 400 megahertz. It is one of the Op-Amps with higher gain-bandwidth product. Typically, it is much lower than that. If we pick, let us say, like our example over here we wanted trans-impedance gain of 1 megohm.

So, let us say R F is 1 megohm, and C F equal to C D equals to, let us say it is 0.5 Picofarad. So, if you plug all of these values into this, so, this is actually 1 Picofarad. So that is about 10 power minus 12. This is RF is 1 megaohms. So that is 10 power 6, so you have a 2-pi term. And then you have a 10 power minus 6 over here.

And again, bandwidth is 400 megahertz, so 4 into 10 power 8, so there is a 10 power minus 6 over there, so that can go at the top. So that becomes 10 power 14. So, you have 4 by 2, so that is 2 by pi, which is roughly about 0.6 or so. So, it is about 0.7. So, if you do all that calculation, you will probably find that this would imply that F 3 dB is equal to roughly about 8 megahertz. So, what does that tell you, if you want to actually achieve this 1 megohm trans-impedance gain, your frequency response is going to be limited to 8 megahertz.

If you want to have higher frequency response, for example, if you are using a distributed sensor where you need, say a frequency response of 50 megahertz, or maybe even 100 megahertz, what you are going to have to do is? You will have to drop this value because your Op-Amp is whatever it is this you picked up one of the best Op-Amps. So, that is available in the market, which has the highest gain-bandwidth products that you have. So, you do not have a choice you cannot get rid of these. So, you will have to drop your R F accordingly.

So, if you have 3 dB, has to be 10 times more RF has to be dropped by a factor of 100 because it is actually coming into the root. So, then you ask the question, if I go back to this application, I want 1 megohm trans-impedance gain, I can get only 10-kilo ohm trans-impedance gain from this stage. So, I need a further 100 to get this overall gain.

So, then I would have to put a voltage amplifier, beyond that, to give me gain of. So, what we are saying is, if this is let us say this is 10 power 6 then sorry, so this is not 10 to power 6 this is. So, what we talked about is 10 to power 4, if you want to achieve 80-megahertz bandwidth, then this has to be limited to 10 to power 4. So, then you will have to limit this to 100.

In practice, you will find that some of these capacitance values are not so low the Op-Amp capacitance also not negligible. So, you will struggle to get even this value, it is going to be lower than that because of all these parasitic capacitances. But that is a game you are going to have to play. So, you essentially have these Op-Amp base trans-impedance amplifiers where we once again, play a trade-off, trade-off between the maximum gain that you want to achieve from the trans-impedance amplifier versus the bandwidth that you want to maintain in doing so.

So, we will look at further issues. So, what we want to know, so, I think we are nicely set up now. That we have covered the front-end photodiode as well as the trans-impedance amplifier section. So, now we can actually go into noise issues, and then see, how noise plays a role in the design of such circuits.