INTRODUCTION

[slide 1] MODERATOR:

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Hello and welcome to National Semiconductor's Online Seminar. I'm Michelle Miller and I will be your host. Before we begin I would like to go over the operation of your seminar interface. Slides will appear in the upper right section of your interface. If you would like the slides to be larger, click the "Enlarge Slide" button. Slides will automatically advance. At the bottom of your interface is an interactive Web browser set to a Web page containing additional resources for this seminar. Questions may be submitted at any time and the presenter will address them as time permits. To ask a question, enter your question in the "Ask a Question" entry window, then click "Submit" to send a question to the presenter. This seminar will be available in our archives within three hours of the live presentation. Finally, National Semiconductor owns and is responsible for all the content in this seminar.

Today's topic is "Photodiode Amplifiers: Turning Light into Electricity." Today's seminar will be given by Staff Applications Engineer, Paul Rako of the Amplifiers Group. Welcome Paul.

RAKO:

Hi Michelle. Thank you so much. My voice is a little scratchy this morning because we had to get up at, what, 7:30? Tanya was here. Boy, us analog people have a hard time with that. I think noon is a good time to start things going. We're going to talk about photodiode amplifiers, that's how you use, usually PIN photodiodes and that can change light into electricity. In addition to Tanya and Michelle, we have Hooman Hashemi, my pal that works at the Amplifiers Group. He's written some application notes on photodiode amplifiers. He's an expert on photodiode amplifiers, so all the hard questions, Hooman is going to handle.

[slide 2] You are more than welcome to send questions as we go along here, they will queue up and we're kind of ambivalent whether we'll interrupt the presentation. If there's a question Hooman thinks relates to a slide, he'll interrupt us and ask the question and then we can deal with it then. Otherwise, at the end of the program we'll have about 15 minutes to do the application.

PHOTODIODE AMPLIFIERS

[slide 3] Right now we are going to send out a polling question. Hopefully all this cool software that we have here is going to work. And the polling question is going to ask if you

are familiar with photodiode amps. We're trying to figure out how much detail to give in this presentation. Are you a general engineer working on firmware and software and analog and digital and so you are going to need the basics explained, or are you an expert photodiode person who knows all the tricks about photodiodes?

So, on our first slide, this is a way you can get a signal from a photodiode. You hang the photodiode up on a two-volt supply and the little double circles with the arrow through it, that represents a current source, if you remember college. And it's a leakage current, that's how I like to think of it. It's a reverse current that comes through that photodiode. The photons go and hit the crystal lattice, they create a hole-electron pair, just like in transistor physics, the holes gravitate towards the "N" material, the electrons gravitate towards the "P" material, and you get a little current. Now you can see that current goes down through a big resistor the way we've hooked it up and it has a one meg resistor so even if you get a few nanoAmps, you can get a signal out of that pin, where we show going off to the right, and if you do the math ten nanoAmperes, one megaohm, you get about a 10 mV signal, so boy, that is simple, right? You get a diode and a resistor and there is your signal.

[slide 4] On the next slide you can see, well, it's not really that simple. Here's the problems you have. First off, diodes, there is an intrinsic resistor. Later on we'll show you a model of what a photodiode looks like. There is an intrinsic resistor in there that creates a leakage current, in addition to the photodiode current. And that leakage current, like most things in electronics gets worse with temperature. So that can be a problem if you're measuring light or getting signal over a temperature variation. You have a big resistor there and that big resistor creates noise. And you know if you want a low noise system you try to keep the impedances, AC and DC, down as low as you can.

We're going to shoot you out another polling question right now, one of the things we are trying to figure out, how many of you are interested in measuring light, like a light meter for a camera, – which is a DC application – versus people who want to get data through a photodiode, like an IR link like the IrDA in your laptop computer. There you are just trying to get bits across, you really don't care about the DC level. As a matter of fact you are trying to get rid of it, you are trying to get the fluorescent light signals and the sunlight and all of that out of the application and just get bits across. So here we are looking at something that started to look simple, but you've got a big noise source with that resistor, it's varying over temperature and you've got leakage currents and 10 mV output. Guess what? 10 mV isn't very useful. You're not going to run that no matter how low the core voltage is on your ASIC, you're not going to be able to switch a logic gate with 10 mV.

[slide 5] So now the next slide, it gets even worse. Okay? Diodes are capacitors too, every diode. There are varactor diodes that they use in radios to actually do tuning. And the way you tune it is by putting a bigger voltage across it. You are essentially pulling the plates of that capacitor apart because you are separating the P-N junctions further and further. [Okay, we are perfecting things. I am beating on the table and Tanya is mad at me. Sorry, Tanya, I won't beat on the table anymore.] Okay, so we've got this capacitance in the photodiode and remember I said if you are doing data applications, well, you are trying to get fast bits through there. Well, the capacitance just slows things down and how much capacitance? Well, on a really fast photodiode it would be two picofarads, big diodes, 50 picofarads. Of course, the more sensitive you want the diode, the bigger you make it

physically, so it can collect more light and then you get the headache of that bigger physical diode has a bigger physical capacitance. So you can't get as much speed through it. So, it works against you. You've got that big resistor, if it was one megaohm, you can imagine even a tiny capacitor against one megaohm's resistance slows things down terribly.

Also remember that that pin going off to the right is a high impedance point. And that's always a pain. What if you want an amplifier that has a little bias current or isn't a high impedance amplifier? Well, that's going to be a problem as well. So you've got changing capacitance, you've got a high impedance thing, now this application that was just a diode and a resistor doesn't quite look so simple.

[slide 6] The next slide we show it's still worse. You've got to make that diode more sensitive, as I said, you make it big. The bigger you make it in order so you can, let's say, work over a bigger distance, or you can have more attenuation, let's say, in a fiber optic, you put in a bigger and bigger photodiode, physically big, well, that collects a lot more light and it converts the light into more electricity, but the capacitance has gone up. So now you've slowed your system down even worse.

INSIDE THE PHOTODIODE

[slide 7] So now, let's look at a photodiode. The next slide shows a cap and a current source, it's inside. We've got a big, giant diode symbol. And you can see, there is a little current source and it works in reverse. There is a lot of confusion, as I go through the Internet. Some people think that depending on the way you hook it up the current reverses magically in the diode. And that gets confusing because some people will talk about using the diode forward biased, like in a certain mode. Well, what they are saying is you can imagine if you hooked a resistor right across that photodiode, the current source would pour into the resistor and it would make the plus pin down at the bottom of that photodiode symbol, which is forward biased in voltage, but remember, the photo current, the things that are created by the photons hitting that crystal matrix, that is always in the same direction. The little arrow is pointing down, it goes in reverse bias through that diode, the "P" side and the "N" side of that junction never switch magically depending how you hook it up. So you can see here, if you put a bigger voltage across that photodiode, you're pushing the "P" side and the "N" side further apart. They repel just like you would expect. So, that is a way, as you remember capacitors are the area, the dielectric constant between the plates, and how far the plates are apart. That's how a condenser microphone works, it changes the distance between the plates and creates a voltage signal. Well here you can put a big voltage across it and lower the capacitance of the part, which is one of the tricks to speed things up.

[slide 8] Now the next slide we're going to show there is a little complicating factor, as always in electronics. The next slide we added a little resistor in there. And that's a more accurate model. That's a bulk resisitivity. It's usually rather high, it can be a gigaohm, but it's 10 megaohms, 100 megaohms. That's what represents the dark current mode. When you run a photodiode with no voltage across it, we'll show you how to do that a little bit later with an op-amp, there is no voltage across that resistor, and no current flows in that resistor, so there is no dark current, and that is a really great thing. Of course, with no voltage across

that diode you have a bigger capacitor because you are not pushing the plates of the P-N junction apart, so now it's a slower type of device than perhaps you would want. It's analog, we all know how much fun analog is. So you are constantly going to have to make these trade offs.

PHOTODIODE AMPLIFIER TYPES

[slide 9] Now, let's go look at the two ways to use a photodiode. There is the photovoltaic mode. The photovoltaic mode is where I was saying you don't let any voltage build up across the diode. You can see the diode is grounded on the bottom and you see it goes into the minus pin of an op-amp. Now, I don't know, we'll look at our polling questions and see how expert the op-amp – how much expertise we have out there for op-amp applications, but even a basic college course should show you if the plus pin is nailed to ground, like we have, op-amp is working, it's in linear mode, it's doing everything it can to keep that minus pin at the exact same potential as the plus pin.

HASHEMI:

Paul, if I may interject.

RAKO:

Yes.

HASHEMI:

It look like about 54 percent of people are familiar with photodiodes and have used them before.

RAKO:

Okay.

HASHEMI:

And in terms of whether they care about DC or not, it's about 66 percent.

RAKO:

Oh, okay, so we should spend more time on this photovoltaic mode. That's when you are going to measure light. There are two great things about the photovoltaic mode, by putting no voltage across that photodiode that means that there is no dark current, so that whole error term, over temperature, goes completely away. Now, if you are measuring, hopefully you've got more time to take that measurement, you care about ambient light condition or something like that, the less voltage across that resistor, actually no voltage across that resistor, means that there is less noise because the current running through there will create 1/f and shot noise. So that term drops out. And you can see from this little slide here, you've got no voltage, you've got one side of the diode is grounded, the other side of the diode goes to a minus pin, there's a feedback resistor and if you remember your theory, the current that flows down through that diode, it'll be going in the downward direction, that's the photo current, reverse bias, that would appear on the feedback resistor. That same current, you assume, for analysis that no current goes in or out of the pin, and so then the photocurrent then goes straight through that feedback resistor and appears as an output voltage. And it's simple math, you can just take how many nanoAmps of photo current you have for a given light condition, multiply by the resistor, and you'll get, if you look at the directions and where the plus appears on that resistor, you can see that the output of the op-amp actually goes up. This is kind of nice, if you have the right op-amp you could run it single ended, if you had a rail-to-rail input, or an op-amp that had a PNP input stage you could run this so that the op-amp was just plus five volts and ground or 1.2 volts or whatever swing you wanted to achieve on the output.

[slide 10] The next slide we summarize the photovoltaic mode. You have no dark current, the other aspect is you get a linear output with the photovoltaic mode. You don't have that voltage across, you get no exponential terms, so it's trivial to correlate the output voltage you get with the amount of light striking the photo detector.

Now we're going to push another polling question out and this involves the analysis. We did it in a seminar, Hooman did a presentation covering noise gain, which is an analysis. Noise gain is a term that we use to analyze a lot of op-amp circuits, but photodiode circuits in particular. And if you have or haven't heard of it we'll maybe touch on it a little heavier if you haven't heard of it.

[slide 11] So, that's photovoltaic mode. When do you want to use it? Well, when precision is important, like if you are measuring light and you want to know how much flux is falling on that photo detector. The lack of the dark current removes an entire error term and that lower noise, you can take, you know, you get more sensitivity. You can take a smaller measurement and the linear output, as I said, makes the calculation trivial.

[slide 12] Okay, so the next thing you want to do, let's say you want to get data across the photodiode amplifier. There, it's the identical slide I showed you before, but you'll notice down on the bottom of that diode, the anode of the diode, you've got it nailed down to minus ten volts. You can see some of the diodes--- I've got a datasheet for one we're working with on a customer, and you can put 20 volts across the diode. It won't avalanche even with that much reverse voltage. And it goes from being a 20 or 30 picofarad device, when you put 20 volts across it and pull that P-N junction apart, it goes down to about two picofarads. And as, you know, Bob Pease, came into my office and was looking at some – gosh, I shouldn't even admit this, he'll be mad at me – I was doing PSpice, he didn't see the SPICE outputs, but I was doing some SPICE, checking out our high speed models and making sure that stuff worked and the noise terms were right, and I modeled the photodiode by putting a 50 picofarad capacitor in the nodes of the amps, so I used a SPICE current source and a 50 picofarad capacitor to model the capacitance, and I had from playing around, I think I had a 500K feedback resistor, which is not uncommon, right, if you are trying to get a volts output and you only have a few nanoAmps, that's perfectly reasonable to have those kind of large gains, large transimpedance gains. And Bob being the intuitive guy, looked at it and said, "Well, this isn't going to go very fast." Because I had prints where I was trying to get megahertz through the thing and you could see that that capacitance is what limits the speed, and it also causes stability problems. We'll talk about that a little later. But, that's a fundamental limitation of the speed, the more gain you have, that capacitor, it means the resistor is bigger, that capacitor slows everything down.

[slide 13] Let's look at the photoconductive mode, where you are putting a voltage across that diode. There, speed is more important than precision and that smaller capacitance allows you to get much faster signals across this system. It's an AC application, as opposed to a DC application. Of course, now you're going to get a non-linear output. Do you care if you're just sending bits across an interface? Not really. You're going to get a little more noise because now you've got the current ripping through that intrinsic resistance, the dark current, so that could be a problem. You're going to have maybe biasing problems because that dark current might change over temperature. But, if you want to move things fast, you bias, you pull that down to a negative voltage. Of course, you could see-- you could, perhaps, hook things up where the plus pin doesn't go to ground, it goes to a midpoint voltage, you ground the diode and then you still have voltage across the diode. You can hook it up in a lot of different ways, but the whole point is you need voltage across that diode to lower the capacitance and make this system work fast.

BIASING THE PHOTODIODE

[slide 14] Now, the next slide we talk about biasing the photodiode. Well, you are going to put a big voltage across that diode, I say a big voltage, it doesn't change in the slide, but remember, it's a current source, so you say, "Well, a voltage change shouldn't change things that much." But, also remember it's a capacitor, and I didn't draw it in this slide, but that bulk resistivity is still there, that dark current resistor is still there. So if you have noise on that bias voltage, it'll sneak right in your system, so don't call us and say we have lousy power supply rejection on our op-amp if you get a spurious signal coming out of your photodiode amp if that noise term is coming in because your bias voltage is real noisy. So we want low capacitance, put a big voltage across the diode, you don't want that to change. Well how do you do that?

[slide 15] Like we showed you before, we're going step-by-step here, you put your minus ten volts on a diode, you've got the leakage current coming through as a dark current, but the primary current symbol there represents a proportional current you get with light input. Use as much reverse voltage as if you want it to go fast, look at the diode datasheet and put as much voltage as you can stand across that diode. I show minus ten here, but that depends. You've got to read those datasheets. We spend a lot of time and trouble doing amplifier datasheets. I'm sure the photodiode people spend as much time and trouble on their datasheets. And you can see the plus pin here is a ground, the minus pin – the whole thing is working as a servo system – the minus pin is at ground, and that means you have ten volts across the diode. And as I explained, maybe you'll put the plus pin at ten volts and the op-amp runs on 20 volts and you could then ground the bottom of the diode and you'd still have the ten volts across the diode.

[slide 16] In the next slide we're going to show you, okay, well, now you've got your biasing across the photodiode, now you want to get signal out of this thing, so you add a feedback resistor. And life is good as we explained. Now, I drew the little current symbol going through the feedback. The arrow shows you the direction of the photo current and you can see a current going from right to left in that resistor is going to make the right side of that resistor a plus. The left side will be relatively minus. But we know the left side of that resistor is nailed to ground, (right?), that minus pin is at common because the plus pin is also at common, so you can see how the photo current is going to raise the output of that op-amplifier from ground up high. The leakage current that you're going to get is going to pick it up a little, maybe 100 mV, 200 mV, a volt, depending on how much gain. But then as light strikes that photodiode you get a positive signal.

[slide 17] So you hook it all up, you're all excited, you go to the lab, or maybe you SPICE it because remember, Bob Pease is right, SPICE lies, especially about a lot of things like leakage current and stray capacitance. So you hook it up and it's oscillating. It's going all over the place. You're saying, "Oh my God, I thought I was going to be able to measure light", and you're getting like this triangle wave, the thing is just screaming in oscillations. What's going wrong? Well as Hooman's seminar presentation explained at greater length, it's going to oscillate because that diode is a capacitance.

AMPLIFIER STABILITY

[slide 18] We'll look at this next slide. Now replace that diode with a capacitor, right, I mean, it is a capacitor. Let's forget about the photocurrents and just look at the AC situation. Anyone with experience in op-amps knows that, boy, that's a mess, you've got a capacitor on the input of this op-amp, it slows down the feedback signal-- that creates a lag, the lag creates an oscillation and everything screams. So, how do you figure out that?

[slide 19] Well go the next slide. We'll see, okay, there we are showing our current source in our diode, the current source and capacitance combined. I want to be clear because the op-amp, the IC designers here, they all talk, think, act, in frequency domain. They would say what this represents, there's an input pole that's a capacitance on the input. If it was an output pole there could be a capacitor hanging on the output of the op-amp, which will also cause oscillations. Pease has got me thinking in terms of time domain. We all look at oscilloscopes before we haul out the spectrum analyzer. In time domain you see it's a lag, and we can remember from feedback theory, lags are bad.

MECHANICAL ANALOGY

[slide 20] The next slide, I'm trying to do a mechanical analogy to show you the feedback problem you get from having a capacitor on the input of an op-amp. You can think of the system as the one little gear is the output stage, that's the voltage being set by the output stage, it's got a little pointer on it. The rack is the output voltage, so it's running the output voltage up and down. The output voltage is fed back with that little resistor and the gear on the bottom is the feedback, the two pointers point to everything, everything is nice and tight, the gears all mesh perfectly. Everything is happy. Now, of course, you know that gear backlash is really either the J-Omega-t. It's not quite the same as a lag.

[slide 21] But, to give you an intuitive feel, we'll go to the next slide with the big red arrow on it. The next slide shows, see how that feedback has a big gap in the gears? Well, you can imagine the whole job of the op-amp, the whole job of the servo system is to keep those pointers pointing in the same direction. Now you've kind of de-coupled the feedback. You've got a capacitor over on the left-hand side of that op-amp, the feedback is coming through the resistor, but it reacts against that capacitance in the diode and it lags, it slows it down. I'm representing that by a gap in the gear teeth on that bottom gear. And now the pointer isn't really following the output voltage. You see what has happened? The output voltage is changing, the resistor brings it back, but the capacitance slows, it lags that change, so now as you can imagine, if you've got a lot of under-the-hood experience like a lot of us, a lag or a backlash in a gear train in a servo system will make an oscillation because it'll try harder and harder, it'll move, it won't see any motion in the feedback system, it'll put more and more amplification, more and more energy into moving that rack, and then all of a sudden it starts moving. Well, it's moved too far, so then it starts oscillating. It goes back in the opposite direction.

[slide 22] So, here is the analogy, we've drawn it. An input capacitance is like backlash in this feedback mechanism. That lower gear has a big gap in it.

[slide 23] I'll pop to the next slide and this is just to make you comfortable with the fact that if you have a capacitance on the output of an amplifier, that also causes problems, especially if you are trying to do things high speed. You have a fast amplifier and it can't stand to have 500 picofarads (even) hanging on the output. The video guys all know this. This is the same kind of problem, but the feedback happens instantly, whatever is at that output pin, the resistor just carries it back to the input side. There is no capacitance over on the input side. But here the problem is the op-amp is trying to change the voltage internally, it's shoveling current into the output trying to get it to change, but the capacitor is a lag term, it's not preventing that voltage from changing . So the op-amp tries harder and harder to change that voltage until all of a sudden the voltage does start changing. Well, it overshoots, it's gone too far and so then it goes back the other way, it overshoots that way, and it just oscillates.

Now, it doesn't necessarily have to be completely unstable and be a free running oscillator, but what you see your capacitance on the input or output or both, which is really what you'll have, it'll ring. You can put a square wave, that's what you'd want to do, either excite the op-amp with the photodiode in the circuit, you could just inject current with a resistor, a 1 meg resistor, or put a light wheel and chop the light going into the op-amp. And you'll be able to see there is ringing on the output and the more unstable it is, the bigger the rings, as those square waves go up and down, there will be a – how do you describe ringing Hooman on a chalkboard? You know, the exponentially damped ringing at every step transition up and down.

HASHEMI:

Also, Paul, it looks like about 54 percent of the people have heard about noise gain.

RAKO:

[slide 24] Wow, that's great. That's great. You guys are amplifier experts. So, let's go to the fix and Hooman talks about this in his presentation, we're going to do follow-up presentations that will be harder, harder-core for mathematics. We're going to get into the calculus of doing all this like we had in our analog seminar series. You've got a capacitance over in the diode, what do you do? You put a capacitor in the feedback system. And you can imagine what is happening, it's always good in analog – even though we are analog folks, it's good to think about the extremes, and when I see a capacitor in a circuit, you think, well, at infinite frequency that's a short circuit, that's just a wire. And when you hook a wire between the minus pin of an op-amp and the plus and the output pin of an op-amp, it's a voltage follower. There's no gain, it's a unity gain device.

So, really, of course, you've got a capacitor in the photodiode and you can kind of see, you know, you can do the impedance as 1 over 2π frequency C, I think a ten picofarad capacitor is, I think, 16 ohms at a gigahertz. So, if you have a 500K feedback resistor, it doesn't take a lot of frequency before that feedback capacitance, even if it's rather small, become predominant. And you can see it's a voltage divider, there is a capacitance in the diode, a capacitance in the feedback system, and that puts a shelf on the gain, it puts a shelf on the noise gain. That's why we asked about that term. You can see every op-amp has a 90-degree phase shift, if that capacitor in the input – in the photodiode adds another 90 degrees, well, boy, you're at 180 degrees feedback, and you've got 180 degrees phase shift. You've got them converging too fast, you get instability. That feedback capacitor, which can be very small, you might, you have to be very careful with layout if you're trying to do something fast. You have to be careful with layout even if you're doing a measurement circuit because of the leakage currents you'll get. But if you can do something with a circuit board, you're much better off than doing air wiring because when you do do it on a circuit board, you're going to get all kinds of stray capacitances that you may not have provided for. So, you have to design this the way you are going to build it.

That capacitance many times when you look at it is two picofarads. Hooman wrote an application of 1244 and he talks about ways to make a little T-Network to actually lower the effective capacitance. Sometimes if you trust your circuit board manufacturer and repeatability, you can make the capacitor with just two parallel plates on the circuit board, put one up and one down in two different layers. And you can get your picofarad or two picofarads there and achieve stability for, essentially, free, which we all like to do.

COMPENSATED AMPLIFIER

[slide 25] Okay, so let's say we got the thing stable, right, you've got it biased up right, you've got it stable, the next slide we say "Biasing the Amplifier." It's stable, but there is this huge DC offset. You're all confused. What is going on? How come you've got so much offset there on the op-amp? Well, the problem here is, remember theory and practice often diverge. Theory says that that minus pin is a perfect pin, that there is zero, that there is no offset voltage, the plus and minus pin are at the exact same point, and there is no current flowing in or out of the minus pin. Well, when they really can do that, you know, we'll all retire here at National. There is always a current coming out of that minus pin and the plus pin as well. That's the bias currents. When you look on the datasheet, there's a reason we put all this stuff in all those 30 page datasheets, the input bias current can come in or out of the pin, you're not really sure, it depends on the particular op-amp. If they trim the bias current, it could go either way because they are using offset trim. They are using a trim circuit or offset cancellation and if it's a MOSFET it could go either way, because there's no current goes into the MOSFET. We'll show you where that current goes. That might surprise some of you.

[slide 26] So the next slide, you might get that offset, there might be no signal at all coming out and what's going on there is you've got the same problem. The bias current might be going in a direction, let's say, coming, let's see if it comes out of the op-amp, then it's going to tend to drive that voltage negative. And what if your op-amp is only biased – the power supply of the op-amp only goes to ground? Well, the output can't go below ground, but the current coming out of that minus pin is going to react, it can't go into the diode. Remember, the diode is a current source, it's a high impedance current source, so any current coming out of that minus pin of your op-amp, it's got to go hunt home, going through that feedback resistor. And that's what creates this big DC offset voltage, and as I've said, it could, depending on the direction of that current, it could drive things up, but if the current comes out, if it's a PNP input stage, like some of our high speed op-amps, well, then it is coming out of the minus pin, it reacts against the resistor, it tries to force the output down, and maybe you are stuck at zero.

[slide 27] So that's the next slide, you say, that's the answer, input bias current, that's what's killing you. It depends, like I say, on what direction it is, whether it rails the output one way or the other and the bias current could be far greater than the photodiode current.

[slide 28] This next slide we say, I happened to look at a datasheet for a LMH6624, it's this great blazingly fast amplifier that we make. It's got – because it's a dielectrically isolated process, it's got a very low input capacitance. Dielectric isolation means all the transistors in that op-amp are in their own little glass boats, there are glass trenches around them, and there's a bonded layer, a glass layer, underneath them. And that means that instead of a junction for isolation, you've got actual glass insulation, dielectric isolation, the beauty of that – there are a lot of great reasons, it won't latch up, it's just a great process, and it also lowers the input capacitance. So that LMH6624 is a really great amplifier for photodiodes, other than it's got 15 microamps coming out of that pin. If you had a one megaohm feedback resistor, which is a little high, but I'm trying to make a point here, well, you'd have minus 15 volts on the output and if you didn't have the power supply for the amplifier down at minus 15, the output would just nail down to the bottom rail.

AMPLIFIER INPUT STAGES

[slide 29] So, let's look at the input stages. I know you guys figure we are supposed to worry about what's inside the little black plastic. But, you have to understand a little of our problems so let's go inside the amplifier. The next slide we are going to show you the input stages. An LM324, it's an old jellybean part. A lot of our parts have a PNP input stage, You can see the little current source at the top. We call that, when you're an old hand -- we call that the tail current because it looks like the tail on a kitty cat or something. So the tail current you set, it splits evenly between the two and when everything is happy and the op-amp is biased correctly, the bias currents come pouring out of those pins. As I say, you can see like 15 microamps. In NPN input stage, you can see, on the right-hand side of this slide, it comes into the pin. The good news, in bipolar technology, it varies over temperature, but not radically, and that will be in the data sheet, how much it changes with temperature.

[slide 30] The next slide shows you JFETs. An LF411 is one of our JFET parts, our competitor, Burr-Brown makes JFET parts, TI makes JFET parts. A JFET input, there is a bias current in, let's say if they were the depletion type NFETS like I'm showing in the diagram. I think our LF411 is p-channel, so the currents come out of that, but notice it is orders of magnitude different. 15 picoAmps, but the headache with that is that is a leakage current going into the JFET, it will double every ten degrees centigrade. Bob Pease stunned me the other day, he got out an old transistor databook from National from the 1980s, the bias current changes with the bias temperature. Now, this isn't so much a problem if you use an op-amp, but if you guys build discrete JFET front ends, which is a common thing to do in photodiode amplifiers, if you run a lot of current through that JFET, you can see in the curves the bias current goes up. So, not only do you have it doubling every ten degrees of temperature, ten degrees centigrade temperature change, but if you run a ton of current through those JFET's, well then your bias current will go up, I think Pease-Cohen effect, Pease found it and a fellow named Cohen discovered it about the same time. So the Pease-Cohen effect can bite you if you try to get a low voltage noise, you run a lot of current through your JFET and now you are in trouble because your bias currents have come up and you've got a biasing problem.

[slide 31] The next slide, let's look at CMOS. I remember asking this a few years ago. I started here about three years ago, I was a consultant for 20 years, and I didn't know all this insider stuff. I said, wait a minute, wait a minute, I'm looking –like-- we have some great parts, LMV751, this is like a low-noise CMOS input op-amp. And I see the input bias current and I say wait a minute, why is there input bias current, does the electrons tunnel through the glass gates of the MOSFET? And the old-hands would all laugh and chuckle and say, no, no, no; you don't realize, every pin of an op-amp has ESD diodes. I've shown these as just discrete diodes there, and the bias current you get on a CMOS part, like our LMV751, the bias current you get there is in inaccuracy, a non-match between the leakage currents of the top side diode and the bottom side diode. And, of course, you can imagine if you move the common mode voltage of that input pair, if you take those gates and move them higher or low, you are changing – you can see, you'll be putting a different voltage across those built-in ESD diodes that are inside the part. And it's not just our parts, every part has this. Of course, my first question was, well, why don't we make a special part that doesn't have the diodes and you have pico-amperes of input bias current. And all the technicians laughed and said, well, if you do leave the diodes out, which we do sometimes for testing, the parts blow up when you just look at them, they are truly impractical to sell that way, just normal handling would blow them up.

So you need the ESD diodes. So, even with a CMOS input, and, of course, the question mark there, which one leaks more? Does the bias current go into that or out of it? Once again, it's nano-amperes or pico-amperes, it's certainly not microamperes, like a PNP or NPN bipolar input stage. But then again you get the same physics problem of it doubles every ten degrees, just like a JFET, because it's all based on two leakage currents.

CORRECTING DC BIAS

[slide 32] Now, correcting the DC bias, this next slide, well, you could use a resistor, right, I mean, you know, you've got 15 microamps coming out of that part, well, you just hang a resistor on it, adjust that resistor, so that the 15 microamps tends to go down that resistor and balance it out and then you just let the line – of course, it changes feedback now, you've got your infinite feedback or your – it's a feedback term, (right?), it's reacting against the feedback resistor. So, it changes that, but, in general, you could at least DC bias this thing. Like I said, a LMH6624 is a fast part, a LMV751, that's a low-noise part. You're going to need a much smaller resistor, LMV751 is a CMOS part so it's got a very low bias current. You could just do that, but then think of – any experienced analog guy should be squeamish right now. It's like, "Oh God, how do I know it's going to be the same bias current on every part?" It does nothing over temperature, right, if that bias current changes radically over temperature, well, then the output is going to change over temperature. So, that's not the best way to do things. Of course, you are going to have much less of a problem with a JFET or a MOSFET input.

[slide 33] Now, there is another way to correct DC bias. That's the next slide. You can servo the error out. You know, some of our competitors, Burr-Brown makes a part that has this built in. So, we prefer not to make something that expensive, we just make a simple system like this, two op-amps, you can use a dual, I used a LMV2011 here, it's our chopper amp, that's accurate to a couple of microvolts.

[slide 37] So, you can servo the output. You change the plus pin. I'm building this stuff, of course, this might work in SPICE, but in real life you would want to build it. Anytime you see op-amps wrapped around like this you start cringing and don't trust SPICE because of all the strays and problems you can get. But, here's a way that, okay, any DC offset at the output, if the bias current out of that minus pin, of the LMH6624, like I say, it could be 15 microamps, if that's trying to force the output, you integrate that, that is what that RC on the output is doing. Since you've got a nice R it doesn't make the op-amp unstable, it's got a higher frequency pole there to deal with. So, you charge up that capacitor, it gives you the average value, that's what is going into the LMV211 there, the average value of the output. But see the other side of that LMV211 is a plus. The plus pin is nailed to ground, so what does that LMV211 do? It does everything it can to make that average voltage at the output of the 6624 ground. And with an LMV2011 you get very close to ground.

I've been playing around, I'm building this stuff, so I'll be able to report to you folks exactly how it works. I'm building some parts that – we make a dual, a LMH6624 {should be

LMH6626], and at first I said, "Well, there is just absolutely no way you could use such a fast op-amp in the feedback and have things stable." Well, it's stable in SPICE, now we'll see. Bob Pease is probably laughing right now. We'll see how it works on a real board. The nice thing is it's a dual op-amp so you can build a circuit with one package. So there is a way. Now you've got the output bias the way you want. Now think about it though, this thing is always averaging. You're not doing to get a DC signal. If you are trying to measure light, like half of you folks are, this circuit is not going to work. Of course, you wouldn't want the minus ten volts across the diode either. But, in many cases, there could be a case where, well, you would want this. Let's say you are trying to measure light but the 60-cycle source of lights are bothering you. And I should warn everybody, if you are using photodiodes, we're getting all kinds of new problems, people calling, "I've got 40 KHz noise in my photodiode. Your parts are no good. What is going on?" Well, guess what? Electronic ballasts for fluorescent lamps, the new ones, they run at 40 KHz. They wanted them to be above 20 KHz so you wouldn't hear it and it would bother you, and it modulates that big fluorescent light in your office that fast and your photodiode will pick it up. So, in that case you want to filter that out, maybe, in your system. Well, you could adjust the poles, you could put capacitance in the feedback of the 2011, you know, you don't have to build it as an integrator like I did there, and take that 60 hertz out. You could roll off the DC enough to eliminate 60 hertz and if you carry your system out in the sunlight, there will be a step change, the system would recover as fast as you designed this servo system and you'd take that offset out, so it would work in a dark room, it would work in sunlight, it would work with 60 hertz or 40 KHz noise terms. So, that is a benefit, but as I say, measuring? Well, that's another problem.

AMPLIFIER NOISE

[slide 34] Now we're going to talk about amplifier noise. We asked about noise gain, it's great that you folks understand noise gain. Half of you seem to be familiar with it. This is the kind of headaches you have. I'm trying to go through the steps of the headaches you get doing a photodiode amplifier. The stability is the first thing. God, it's screaming all over, you can't even get an output to settle down. You hang that little capacitance in the feedback; as a matter of fact if it's a panic, you hang a big capacitor, just slow the thing down first and get it to settle down. Worry about how fast the response time is later. If you are taking a measurement and you've got seconds, well, you could put a huge capacitor in the feedback and make it unconditionally stable all the time. Well, you've got it stable and then you see there's bias problems, we just talked about the bias problems you get. Well, geez, you've got to get that output centered and stabled and servo'ed to where you can use it, but then there is always one thing you fight because photodiodes, it really isn't a big signal, and you are fighting noise. And you are constantly fighting noise with these amplifiers.

Now, what's so tough about noise in a photodiode amp? Well, it's a transimpedance application. You can see in this slide that the plus pin is nailed to ground, the minus pin is doing the work, it's got the photo currents, you know, passing through to the feedback resistor. You look at the minus pin. There is both current noise and voltage noise. Equivalent input – we refer everything back to the inputs to make your life simple. The equivalent input current noise, nano – what is it? PicoAmps per root hertz often is an order of magnitude term. That comes out of that minus pin, well, there is no way that noise of current shaking in and out of the minus pin, there is no way that that noise can be distinguished by your system from the actual photo current coming through the diode. It's a pure error term. And you can see since it's on the input it gets gained up, so that's a real mess. This is a situation, and this is one of those intuitive things, the old hands seem to know that, I strike my forehead of course, if you are running a lot of bias current you tend to have more bias current noise. So, JFETs tend to be good for current noise. PNP stages, where you are pouring a lot of current out of the base, well, you've got a lot of current, you only need a small percentage of it to be changing as noise, and you get a lot of noise current.

So, on the minus pin you've got current noise problems. The plus pin, do you care about current noise? Not at all. It's nailed to ground, it's zero impedance. So, any current coming in and out of that plus pin percolating around, it doesn't do anything to the output, it just goes right in to ground, it doesn't care. Well, what about voltage noise? There's an equivalent – both pins have equivalent current and voltage noise terms. That voltage noise appears on the plus pin and it just shows right up. You know what happens when you wiggle the plus pin of the op-amp, the output wiggles just the same, it's like a bias. So the voltage noise matters, it's not gained up as bad, but that matters on the output, and that's the hard thing.

[slide 35] This next slide summarizes the problem. Low current and low voltage noise in the same part is tough. The JFET amplifiers have low current noise, but you'll see they'll have higher voltage noise. Bipolar amplifiers, they are good for low voltage noise, anything where you run a lot of current through it tends to have lower voltage noise, and then I wanted to warn you, Choppers can cause a problem. Like our LM – you guys doing measurement, if you're using an LMV2011, it's a fabulous part, it's got relatively low bias currents, but remember it's a Chopper. So there are switches, there are semiconductor switches in the front end of that part and they are percolating, 25 KHz, 30 KHz, that's the inherent chopping frequency of our particular part. Competitors' parts use different frequencies. But, that chopping into a high impedance, if you've got 500K, that's going to be trouble, because there's enough AC charge injection in and out, that's always a headache the IC designers have, charge injection in those switches, and that shows up into a high impedance node. Now, if you've got – we did an app-note. Rick Zarr, my buddy, did a design idea. He used an LMV2011, but look at the resistors and look at the capacitors in that circuit. (See, it's analog, so everything applies.) They are low enough so that the input chopping noise, that input AC impedance, doesn't affect that circuit. So, that's a case where, yes, you can use a Chopper, and our 2011, you'll never find a more cost-effective way to make a very precise measurement. And, of course, the beautiful thing about a Chopper, it corrects its offset voltage over time, over temperature, over part-to-part drift, so that's a method that you can look at if you have low impedances. Use a big diode, collect a lot of current, have lower gains, lower impedances, maybe even add a capacitance, you know, a big feedback capacitance, that can absorb some of the chopping energy, some of the AC noise coming out of the pins.

[slide 36] Now the last slide, well, not the last slide, but the last design slide here, this is a composite amplifier, a compound amplifier. Hooman showed it on his presentations on the analog seminar, I shamelessly stole it. As my mentor said, "It's not stealing, it's making use of the prior art." So, here is our famous slide 36 that caused us a lot of grief because Microsoft PowerPoint didn't want to display it in presentation mode or print it out, but we've got it for you here. You can see what we've done is we've built a little JFET – we're op-amp designers, this is a little JFET front end now. We are using two N-Channel depletion mode JFETs, 2N5486's, and as Pease pointed out, the beautiful thing about this circuit is, well, you're getting low current noise because JFETs have low current noise. That's why our LF411 is a good candidate if you are trying to do something with photodiodes. But a LF411 is kind of slow, I think a LF356 is faster, that's megahertz, but with a lot of gain, remember, you are fighting that gain bandwidth term, so you need so much gain even with a 200 MHz op-amp you might only get two or 10 MHz of actual transimpedance gain going through it. Well, with the JFETs you get your low current noise, you run a ton of voltage--I'm sorry--you run a ton of current, you can pick that R_L, 2K is what we are showing here. You want to lower the current [should say voltage] noise, just run a lot of current through. You bias it to run a lot of current through those JFETs. And then the normal, there are things in our seminar. We'll talk about how you get the normal stability terms with those little dotted boxes show you. You can see there are two loops in this, a close loop around our LM6171, that's a great part. The LM7171 is a faster part yet, and that's a plus or minus 15-volt part. So, you might want the big output swing on it, so you get a bigger dynamic range.

[slide 37] So, you can build compound amps. Bob and I are talking, we're going to build some circuits now in the next few months. You can use a single-ended, you could just use a single JFET out there and run it into the op-amp that way and nail that plus pin to ground. So, we'll start building all this stuff and explain it to you as we go along.

[slide 37] We wanted to give you some parts, once again, shamelessly stolen from my buddy Hooman in the op-amp seminar. Here are some parts. Hooman did a smart thing, which is to be expected because he's a smart guy. He created a figure of merit to help you. Now, I just explained, you care about input noise voltage because that plus pin is hooked to ground. So, you see, that is the first column in all these parts. The next column is input noise current. That's important because of the minus pin, right, that's just a straight error term. The input capacitance, remember, the capacitance of a part appears just in the system, in the servo system, it appears just like capacitance in that diode. It adds, it's in parallel in the AC concept. So, the lower the input capacitance, the better off you are. You can see those LMH6624 and 26, the 26 is the dual, you can see – I love those parts, look at that, our dielectric isolation has got it down to 0.9 picofarads of input. The bias current? Well, that's where you get hurt. Here's 20 – Hooman probably took the max over temperature, 20 micros I was talking about 15. You can see an LF411, well, 200 picoAmps, right, that's a JFET. The LF, the "F" is for FET.

Gain bandwidth product, well, for you guys who are trying to get data across this system you are going to care about how fast the op-amp is. You can see 500 MHz for the LMH6626s, the LF411, well, only four. The LMV751, that's a part I love, you get five through there. It's a CMOS input so you can still see you get fairly low, even less bias current through that, out of that guy than you do the 411, the LF411. Then what Hooman did because he's a smart guy, to help you out, he made a figure of merit over in the final right-hand column, which is the gain bandwidth product. If you want to go fast you put that in the numerator, so the bigger this number is the happier you are. You want the input capacitance to be small, so you put that in the denominator. And so here you can see a figure of merit where if you wanted something to go fast, well, the LMH6624 or 26 would be a great part.

You've got to deal with the bias currents, you've got other problems with it, but that's a part that you could move a lot of data through. If you are doing measurements, well, LMC662, well, who cares if it's .3 as the figure of merit. You guys taking measurements, well that would be part you would want to look at.

CONCLUSION

[slide 38] So, let's conclude up here and we'll have some time for some questions, we're running a little long. Photodiode amps are tricky, we are going to be covering this subject in greater detail over the next year. Don't be discouraged, (right?), we're starting with the basics here, we're trying to get you the intuitive feel. You see no math, we're not going to try to give you math right away. We want you to understand how it works, then we'll show you all the cool math to figure out – and it's very iterative, it's a very iterative process. You pick a photodiode, pick an amplifier, get your capacitances, run through all kinds of integrals and differentials, get your circuit performance, and that's just the analysis stage. As Bob Pease will warn you, you've got to build the thing to make sure that it actually works. Second point, well, it really matters if it's a DC thing, that's one whole way to look at it, if you are trying to move data through a photodiode that's a different animal, that's an AC application. Third point, trial and error, yes, you are going to be building it, you should build it on boards. Use my friends at Proto Express, Ken Bahl, he'll make you a quick circuit board and you can use that to really see how it will work in a true application. Now, if you want to be like Bob Pease, you can wire it in air, but realize you don't have any stray capacitances there. It's an ideal system and they can't make those little air-ball circuits in manufacturing. So, a lot of trial and error, study. We're going to give you some references on the next slide, to help you through this, as well as you future presentations.

Applications is here to help you. You know, even if you are only doing a couple, we don't care, you don't have to be a million-a-month customer, we are here to help you people. So if you have any issues with photodiodes, we're looking for any input from you also, if you'd like to write in and tell us, "Hey, I'd like this kind of amplifier." We'll be glad to look at it. Even if you don't have huge volumes, if we think that it's a nice amplifier and it makes sense for the reasons you specify, we can look at putting it in production.

[slide 39] So, what other resources do we have? Well, good old AN1244, Hooman wrote that, it's got some neat – it shows how to use a current feedback amplifier in a photodiode application, it's got some discretes on the front and you'll see it's a – hopefully you'll understand it a little better now that you've got this basis down. WEBENCH, we've got our on-line WEBENCH that can help you with amplifiers. You can model this little capacitor in the front, like I did in SPICE, and instead of using a real photodiode model, what's important is that capacitor, that's what kills you. And then to simulate the photo current, well, you can use a voltage source and a one meg resistor to simulate the photo current in the diode. A few books, "Op-Amp Solutions" by Jerald Graeme, that's a classic book. "Photo Detection and Measurement – Maximizing Performance in Optical Systems," Mark Johnson, another great book. And "The Photo Detector Book" by Silvano Donati. So all those resources, we are here, there is a ton of literature out there, and what we're going to do though in the next year is actually build a bunch of circuits and carry you through the real world problems and what it takes to get a real photodiode application working.

[slide 40] So, the final slide here, thank you, thank you so much. like I say, we want to hear from you, we don't just want to lecture, we want to hear what you guys need to know about photodiodes. We want to know what kind of amplifiers you want made. Here is a couple of email addresses, feedback@nsc.com, there is a technical journal, National Edge, there is that address, and we've got a newsletter and if you want to make sure you catch not only our future seminars on photodiodes, but seminars on all kinds of subjects across our whole product line, you can use those links. And now I will turn it over – oh no, I'm sorry, there are some questions.

HASHEMI:

There are some questions for you.

RAKO:

Oh, okay, any good ones? Why don't you take them.

HASHEMI:

Yes. To compensate for input bias current, why not put a resistor equal to RF in a non-inverting input?

RAKO:

You can do that, it moves the bias up though, right? It's going to change the bias point, it also creates noise. So now, since you've got – that's a great question because the person understands op-amps. It's a perfect, a classic way to cancel out bias current in all the basic op-amps. What bites you in a photodiode is it's going to be a big resistor and that big resistor is going to have a lot of noise in it, and now, remember, that plus pin, you've got a "bye" on current noise on that because it was nailed to ground. So then you're going to want to look at, okay, maybe put a capacitor and a resistor. The resistor handles the DC bias current, the capacitor handles the current noise at high frequency, but you're still going to get bit at low frequency and that's where that 1/f formula, and if you look at the datasheet charts, you'll see that noise current and voltage noise, current noise, are always at the worst. But, it may work in your application, that's a great point. That's another way to do it. Anything else?

HASHEMI:

Yes. Somebody else is asking if it's equivalent to put the photodiodes on the plus terminal – I think that's what he's saying.

RAKO:

Sure, sure. That's what I was saying. You could do that. You have to think about the issues about noise. Like, if the plus pin, you know, any way you get voltage across it, any way you see some of – I work on laser diode drivers for DVD players. Sometimes they build a little photodiode into the laser and that's how you modulate and make sure that the laser stays at an average power, a given average power. There they just tie it up to the high side, because they know the current coming down through it will – you can then do the trivial circuit to make that. What you have to worry about in all these applications is, remember, usually the plus side is noisier, so you'll have a lot of voltage, a lot of maybe digital noise, switching noise, and, excuse me, that diode is a capacitor. So, if you need high frequency response, some of the noise on that plus supply might go through the diode capacitance. But that is another great point. We've got some clever people out there. That's a perfectly fine way to do it, realizing though, this is where people get burned. If you do it on a lab supply on your bench, you are all happy, you are all proud, I've got a great circuit, it goes into production or goes integrated in the system, and some digital guy gives you some horrible five-volt supply that's got all kinds of noise on it, and not only do you get it leaking in because of power supply rejection ratio in the op-amp, it'll come pouring through the rest of your system anywhere you let a component touch that high side. Anything else, Hooman?

HASHEMI:

Yes. They are asking also like a survey, a survey of what photodiodes are available in the market?

RAKO:

We, I think we are pushing links out, Tanya and Michelle will help us, for some photodiode manufacturers. We were talking about maybe putting – Centro Vision was one that I had, that I found. I did a Google search. There is a ton of stuff and really, once again, this is a good question because the person understands you've got to start at the beginning and you are not going to be successful unless you really understand all the quirks of the photodiode. I do Google searches, that's a good question, we can look at pulling together a general little help sheet to help you guys look at everything we learned. Since why duplicate work, right? We're engineers, we want to be efficient. So, anything that we learn we'll make sure that we can get that to you folks for that.

HASHEMI:

And then a couple of questions, I'm not sure if you'll be ready to answer them or not. But somebody is asking about attenuation of intermittent signals in free space. They are saying that if we're doubling the distance, they are getting 12 dB of attenuation versus the 6 dB that we would normally expect. I don't know if you have an answer to that.

RAKO:

That's spherical. You've got to look at the output. If it's just in free space, it should be worse, right, it's a sphere that you're lighting up, it's not a doubling distance, it's a cube function, so you get that headache. The other thing that I found is it's humidity, right, if it's infrared, it depends on the spectrum, if it's – I did a CO_2 detector for the space shuttle, and there it uses photo-piles and chopper amps to detect carbon dioxide absorption and the IR, they use a particular bandwidth of IR and filters, and it's very absorptive. The carbon dioxide absorbs the IR and that's how you figure out the percentage of CO2 without chemicals. And the headache is you've got to pick frequencies, you've got to pick right IR frequencies that aren't related to humidity (and there are other attenuations). So, you can look at that and make sure, you know, feel free to email us and we can gladly help you with that and try to figure that out.

HASHEMI:

Okay. And then there are some general questions about when the presentation would be available on the Web for downloading and saving and I think that's about three hours.

RAKO:

Yes, when I turn it over, we're going to turn it over for Michelle to say good-bye and she can explain all that good stuff. They are the marketing, super smart experts on that.

HASHEMI:

One last question. Somebody is asking about what about three gigahertz, applications after three gigahertz?

RAKO:

Funny, I'm kind of working on that. Pease and I are both – that's when you call in Bob Pease, that's what I did. It's do-able, (right?), I assume it's a fiber application, that's a data application you're doing. It really gets hairy. I can tell you what we're going to look at. Short channel MOSFETs like they use in the front of scopes. There is even one in Digikey that I found, I think NEC makes it. We're going to look at JFETs, we're going to look at – of course, these are the things you can't, like we can have some JFETs made and process here and play around with that. But, that's really the hairy edge for electronics. When you see things going really fast in fiber optics now, they are doing things like Erbium doped fiber, where you never turn it into electricity. You pump the Erbium doped fiber with laser diodes and you do amplification in the light mode. So, three gigahertz is, you know, we're going to be happy to even get a gigahertz at first. But three gigahertz is a tough, tough application, but call us up and we'll work on it together. We're more than happy to help.

Okay, I think we'll turn it over to Michelle now and Michelle will close up. I thank you so much for being with us and stay tuned to National. We're going to have lots of good seminars for you. Thank you and good-bye.

MODERATOR:

Thank you Paul and thank you Hooman. Thank you everyone for joining us for this seminar, Photodiode Amplifiers, Turning Light Into Electricity, brought to you by National Semiconductor and IDT. This seminar will be available in our archives shortly and this concludes today's seminar. When you close your seminar window and survey form will appear, please fill it out and submit the survey form. Your answers to this survey will help us in the development of new products, as well as future seminars. Thank you for attending and have a great day. (END OF PRESENTATION)