CMOS RF Integrated Circuits
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Module - 12
RF Power Amplifiers
Lecture - 37
Class A, B, C Power Amplifiers

Hello and welcome back to CMOS radio frequency integrated circuits today we are starting a new chapter new module about power amplifiers and I am planning today to basically just introduce to you the idea of why we need a power amplifier what the deal is and what are the requirements of the power amplifier and then we will discuss class A class B and class C power amplifiers. So, the power amplifier is basically the last block just before an antenna on a transmit chain if you are building a transmitter.

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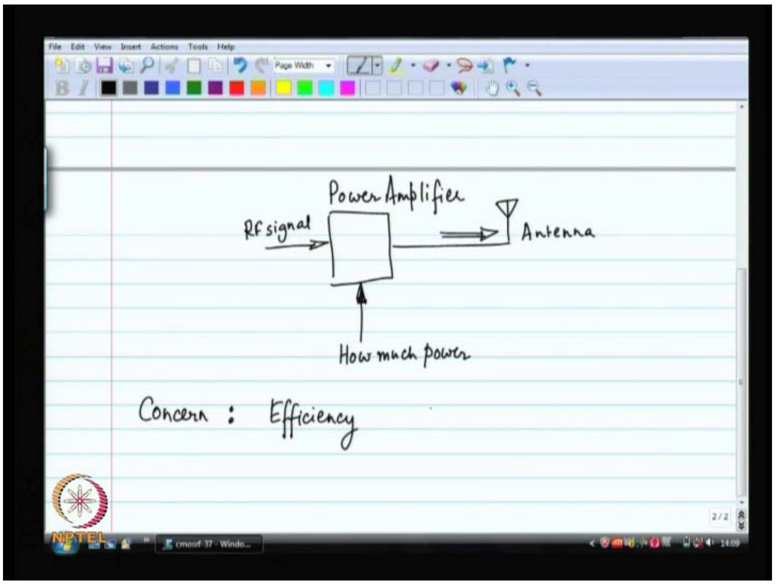

Then you will have some RF signal then you will apply the RF signal to the power amplifier and the requirement of the power amplifier is basically to pump out as much energy as possible through the antenna and broadcast the message.

So, this is basically the scenario you need to broadcast some message the message comes in a modulated format you already have and RF signal over here you have done the modulation you have done the mixing you up converted to radio frequencies and then you just need to amplifier and you need to pump out as much power as possible. So, that here messages received by whoever try to receive your message. Now, in cell phone networks there is a slight issue. So, typically what you can do is you can conceive of just blasting out as much power is possible and hopping that whoever you want to reach is going to get it going to receive the message. Now, in cell phone networks things are very optimum. The network is going to tell you the pleased broadcast not more than this much amount of power why because if you do broadcast more power, then it is going to reach next cell it is going to cause gas because it is going to interfere with someone else is communication.

So, the cell phone system is based on frequency reused. So, different cells different hexagons you remember different hexagons will be using the same frequency over and over again that is how we are can accommodate so many users. Now, if you broadcast too much power then your message is going to heard in some other cell which is not intended it is going to go beyond the your base station and that is going to cause problems, if you send to less power then of course, your base station is not going to receive it. So, your base station has some idea of where you are how does base station have any idea of where you are how far away you are from the base station, well your phone is going to tell the base station that look I received.

So, much amount of power this is the quality of the channel and from this report of your phone back to the base station. The base station can estimate where you are once the base station have an understanding of where you are if knows exactly how power you need to send to the base station. So, that you do not overdo things now this is the general scenario. However, under CDMA systems CDMA Code division multiple access. So, under CDMA systems this requirement is much more stringent. So, CDMA white band CDMA by CDMA, I mean all cell phone systems that use code division multiple access.

Now, this requirement of how much power you have to transmit is much more stringent under CDMA systems, why it is because if you send too much power then if you send even half db more than needed then you are going to over shadow what someone else is saying remember in CDMA everyone there are lot of users not everyone a lot of users using the same frequency they just have different codes now if you send too much power then others who are also using the same frequency get over shadow.

So, the idea is that when your signal reaches the base station the amount of power gets from you should be equal to the amount of power it gets from everyone else only then can base station do a reliable demodulation of the signal. So, this is the very stringent condition in CDMA systems and because of this condition for a long time CDMA had a bottle neck could not be implemented in the real world because of this particular bottle neck for a long time. So, the CDMA has a concept was known long back several decades back. However, it was not implemented in real life and in real world because of this particular issue of power control.

So, therefore, if you go back to the block diagram over here someone out there has got to be telling you telling the power amplifier, how much power. It is not just 1 input and 1 output there are 2 inputs one is the RF signal of course, the second is how much power does the power amplifier need to broadcast.

It should not overdo it is job right. So, this is the generic block diagram now what is the main concern as for as power amplifier goals if you want your mobile hand set to have a long battery life you do not want to recharge every night you do not want to be recharging every hour, you want to charge your phone and when walk around with your phone for 2 or 3 days and then come back and recharge it. Now, for this to happened you have to realize that one of the largest consumers of powers in a cell phone is the power amplifiers why because it is broadcasting power you this is where you are really reaching out to the base station. So, you have to invest in terms of power into the power amplifier you have to put out power through the antenna.

Now, for that reason the power amplifier is the hungriest as for as power consumption is concerned. So, therefore, it is very important for us to I am clear understanding of the efficiency of the power amplifier. So, as for as the efficiency of the power amplifier goes every point 1 percent every 1 percent every half percent matters right in your power amplifier design you have to be efficient as possible and your design is going to win if you are the most efficient.

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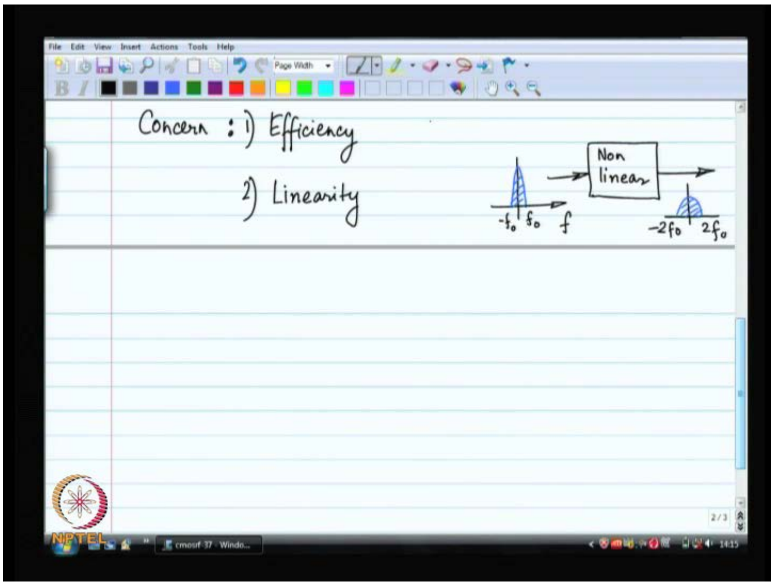

What else matters as for as the power amplifier is concerned efficiency is something very important to you because you want to have a long life for your battery what else is a concerned as for as the power amplifiers concerned.

Let us understand it as follows, the power amplifiers are pumping power out into the antenna the antenna is a linear component, what is the linear component? you know the definition of the linear system. So, the antenna is a perfectly linear system if input to the antenna is at frequency f the output of the antenna is going to be at the same frequency f no harmonics are created the power amplifiers is the last active block in the transmitter, which means that if you want a clean output distortion free output of the power amplifier, then the power amplifier itself has to be distortion free it just could be that the input to the power amplifier the RF signal is perfectly clean the power amplifier is badly lonely near and it is going to introduce large amounts of distortion and choke the system why is it going to choke the system because distortion if you have a single frequency input, then distortion will cause harmonics. However, the input the RF signal is not just one frequency is it just one frequency.

No it is not just one frequency it is arrange of frequencies right with has a bandwidth the bandwidth could be 100 KHz bandwidth could be 2MHz for a WCDMA system or 100 KHz for a GSM system, that is the bandwidth of the RF signal, but it still have the bandwidth it is not one single frequency now whenever you have a band of frequencies think about this I am going to do it at base time. So, whenever you have a band of frequencies this is the input to a non-linear system, how is the output going to look like the output will be is made.

So, this is because of squaring many more different things this is just because of squaring if you do a cube action cubic non-linearity then other things will happen etc. So, a non-linearity does strange things if it is a single tone then non-linearity creates harmonics, but our input is not a single tone our input is a range of frequencies and what this is going to end of with not something that you want it is called distortion.

So, an important concerned as for as your power amplifier is its linearity how linear is the power amplifier. Now, it turns out in any other concerned efficiency tells you that if your base station as ask you to transmit 1mv of power how many milli volts are you spending that is what efficiency is going to tell you linearity is something else linearity is just to make sure that your signal goes through without any problems and also to make sure that you do not create problems for others. So, because of both of this linearity is something very important for us. So, are there any other concerns that come to your mind anything else?

Let us stick to these to I do not recall any other major concerns as for as the power amplifier is concerned of course, how much gain it has is concerned, but it is irrelevant once you specify the amount of power at the output. So, now, let us look at different architectures of the power amplifier, but before we go into different architectures of the power amplifier, I am going to give very generic structure.

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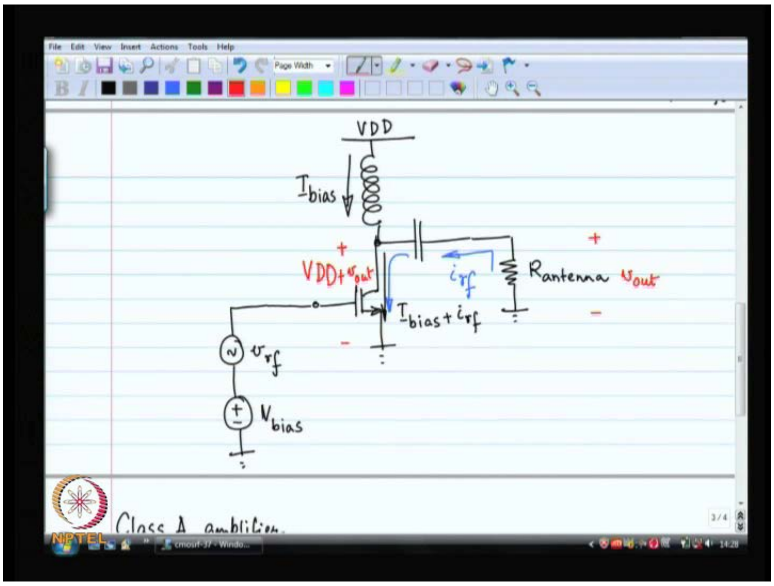

So, the very generic structure which is important for lot of the classes of the power amplifiers is basically something that is looks like this. So, R antenna is the radiation resistance of the antenna.

So, just can consider it as a discrete resister there is single MOSFET over here that I have drawn and there is a one inductor and one capacitor let us say that this inductor and this capacitor both are so big that the inductor is short circuit for DC and open circuit for AC and the capacitor is the short circuit for the AC and open circuit for DC. So, is this transistor biased, well the V bias is the bias voltage for the gate and let us going to be some bias current which we are going to call I bias. V gs of I bias causes a current I bias that current is coming through the inductor without any drop and you got the full supply voltage across the drain and the source. So, this is the basically the situation. Now, I am going to use this particular block diagram for class A, B, C all of them everything I am going to use the same block diagram.

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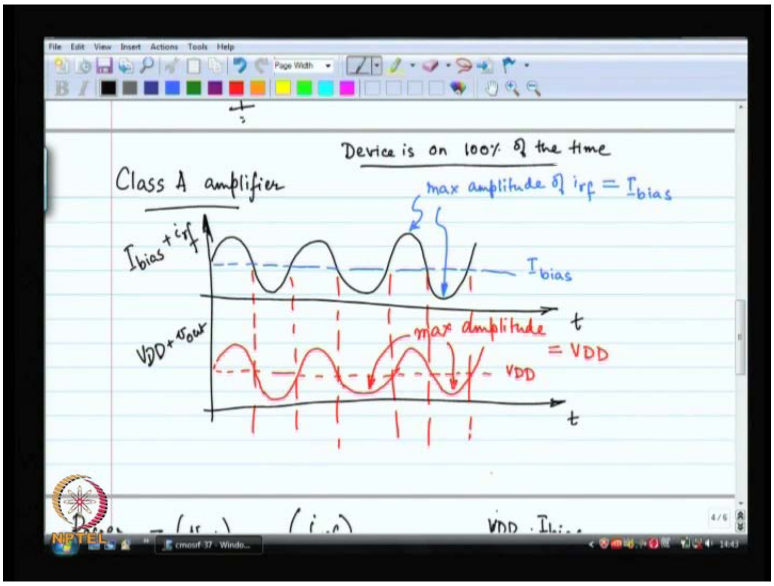

So, let us first discuss class A amplifiers now, class A amplifier is the most straight forward generic amplifier. The class A amplifier is the most straight forward generic amplifier where basically the transistor and the MOSFET that have used over here is in saturation all the time.

So, MOSFET is in saturation in all the time this is how we build amplifiers we have learn to build amplifiers in your analog circuits class and it is always in saturation that is what I am going to do over here our MOSFET is always going to be in saturation it is going to me some gain I do not really need to think about the gain in terms of the voltage I want to output of certain amount of power think about the power do not think about the game in terms of voltage we want broadcast as pump out a certain amount of power into the antenna. So, if I plot the output voltage or the output current.

Not the output current let us first label it. So, the signal current is I rf that is the signal current and the current that is going through the MOSFET is I bias plus I rf So, capacitor make sure that is its S short circuit for AC the inductor make sure that it is an open circuit for AC. So, all the I rf flows directly through the MOSFET this is number one. So, I am going to plot as a function as time this particular quantity I bias plus I rf and the other thing that I am really interested in is the voltage the voltage time is the current is basically the power you have generated the power you have for deliver to the load not generator. So, that is also something that I am interested in and what is going to be the voltage across the drain and source of the MOSFET it is going to be V DD plus V out. I am going to plot the other quantity that I am going plot is V DD plus V out. Now if you consider these 2 plots what is required for the MOSFET to always be on in strong in version and in saturation what is needed for this to happen.

So, first thing that needs to happen is that the current going through the MOSFET has always got to be more than 0 for the MOSFET to be on. So that means, this waveform suppose it is a sinusoid, that means, that this wave form will have an average of I_{bias} and the maximum amplitude of the RF current the signal current should be equal to how much equal to the I bias why because the current has always got to be the net current always has to be more than 0 and at the trough of this wave form we have a problem it is approaching zero. So, we have to make sure that it is more than 0 which means that the maximum possible amplitude of I rf is equal to I bias when it really touches 0. Now when the current is the largest when the current through the device is the largest the voltage across the device is the smallest or the largest why is this current changing because of V gs.

I like this grid lines when I do my plot because otherwise you need to know how you are lined where your alignment markers also it is important. So, the voltage is going to be maximum when the current is the minimum and vice versa and in any case to maintain the device in saturation you have to guarantee that the voltage drop V ds has to be more than the over drain voltage, this is your first ordered MOSFET model the V gs has to be more than the over drive voltage to maintain the MOSFET in saturation. Now this unfortunately works only for strong inversion other regions of inversions no longer works. So, if we over drive this equal to 0 or less than 0 it does not mean that can be equal to 0 or less than 0. So, there is an absolute limit to allow your drain to source voltage can be some people can say about 5 or 6 times the thermal voltage. So, about 125 and 150 milli volts are absolutely needed to maintain the MOSFET in saturation. Now, in this analysis let us make an assumption that the absolute minimum voltage needed to maintain the MOSFET in saturation is 0 volts that is a very incorrect assumption, but I just want to demonstrate what the problem.

So, let us make that assumption and move on. So, in that case what is the maximum amplitude of V out. So, similarly over here the average of V dd plus V out has got to be

V dd which means that the absolute maximum max amplitude of small V out is V dd So, what is that mean what is the maximum power deliver to the load.

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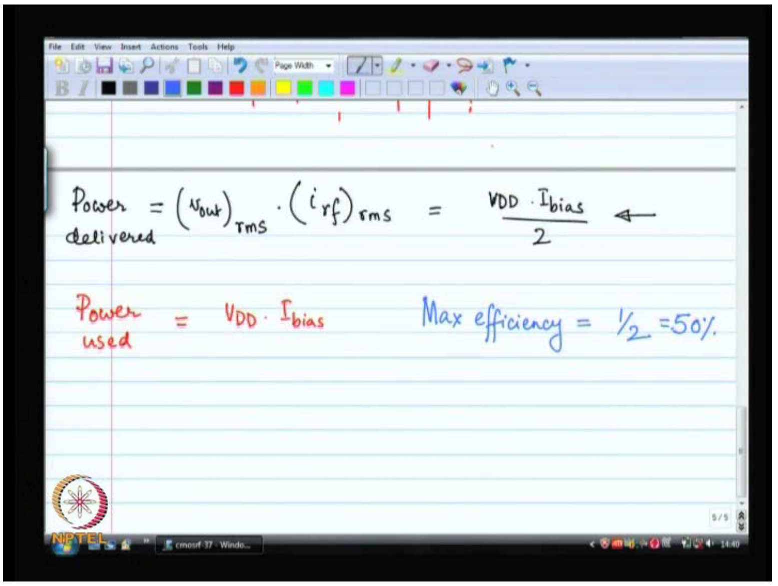

That you can deliver to the load the power deliver to the load is the amplitude of V out actually no it is the r m s of V out times the r m s of I rf. Now, the r m s of V out is equal to the amplitude of V out is V dd.

So, the r m s is V dd by root 2 and the r m s of I rf the amplitude of I rf is the r m s is I bias by root 2. So, therefore, absolute maximum power that you can possibly deliver is V dd times I bias by 2. Now things will only get words once you recall that the absolute maximum amplitude of V out is not equal to V dd it is got to be something lesser than V dd why because you have to keep some head room we said 125 and 150 milli volts you absolutely need. So, much if most probably your device is in strong in version in which case you need the over drive voltage as the head room I mean we do not know how much over drive voltage have chosen. So, accordingly that will limit what you are absolute maximum amplitude of the voltage S the signal voltage S. In any case we said let us proceed with the assumption that it is equal to V dd. So, in that case the absolute maximum power deliver to the load is V dd times I bias divided by 2.

Now, the next question for you is what is therefore, the efficiency of the circuit what is first of all what is the power consumed by the whole circuit does V bias deliver any power to this system no it is driving a gate it does not take any current is not using up any current. So, let us forget about V bias. I think we do have a problem here this is got to be in phase would not be out of phase it does not matter for this particular analysis since it is in phase I think I had confuse the signs. So, what is the power consumption of this circuit what is the total power consumed the power is being consumed from the power supply.

The power supply is delivering a current I bias from voltage V dd so, therefore the power supplied by the power supply is equal to V dd times I bias and therefore, the maximum efficiency is 1 by 2 which is 50 percent this is horrible. So, if you want to broadcast 1 milli volt of power you have to burn 2 milli volts of power as you broadcast 1 milli volt and you waste 1 more milli volt.

This is really bad news as for as the power amplifier is concerned now what we just discussed was the class A amplifier and this is what it is the definition of the class A amplifier is a vector the transistor is always on the MOSFET is always on and because the MOSFET is always on it is always going to use the bias current. So, V dd times I bias current is the power consumed the power deliver to the load unfortunately is a V dd times I bias by 2 that a life.

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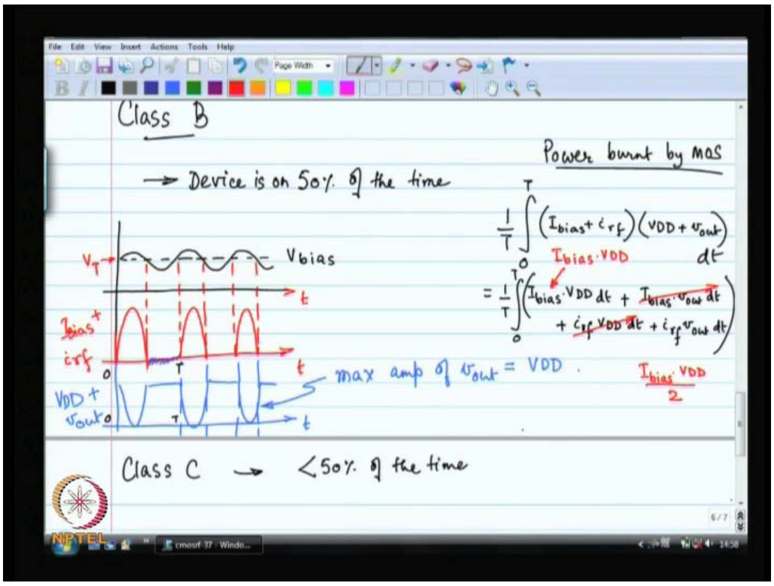

Let us move on to the next 1. So, next 1 is called classic B and here the idea is that instead of having a MOSFET on 100 percent of the time let us keep the MOSFET off half the time on half the time and then what we are going to do is instead of this particular load that I have drawn over the load is just R antenna instead of that particular load if I keep the MOSFET on for some time off for some time it is going to create a lot of distortion lot of harmonics are going to show up. So, I am going to use an attack which is tuned to the frequency of operation to the frequency that I am trying to transmit. So, I am going to filter out all the other harmonics I am going to keep only the one that only the fundamental. So, let us take a look at the class B amplifier.

The class B amplifier definition is the device is on 50 percent of the time class A amplifier the definition. So, this is basically going to define which class my amplifier is how much what is the percentage of time it is on. So, 100 percent it is class A 50 percent it is class B then we have got something called class C which is less than 50 percent of the time and we have got class A B. So, all kinds of names class A B is between 50 percent and 100 percent. So, it is actually one device is on 50 percent of the time we are going to use two devices to do the job in class A B. So, let us look at class B.

So, class B is basically the same circuit it is just that now I am saying that let us not have such a large V bias voltage let us reduce our V bias. So, this is where the tweaking this is our control now V bias now. So, let us reduce bias. So, that the device is on for 50 percent of the time by definition class B is precisely 50 percent, but around 50 percent let say and what is going to happen then. So, first of all what is the gate voltage.

The gate voltage looks like this. So, what we are saying is that lets have a let us assume a crewed MOSFET module where the device is on when the voltage is above V_T and the device is the gate to source voltage is above V T device is on gate to source voltage is below V T threshold voltage device is off. So, let say that with such a crewed MOSFET module we make sure that V bias is exactly equal to V T a threshold voltage and as a result when you apply the signal. Part of the time, the device is on and it conducts I bias amount of current and the remaining half of the time the device off and it conducts no current. So, during this part of the time when the device is on its going to conduct I bias plus I rf amount of current and the remaining time it is not going to conduct an eight. Now, yes we did this we I think I am confusing over here this is going to be out of phase. So, please double check that it is going to be out of phase the voltage at the output is going to be out of phase with a current it is an inverting amplifier.

So, now, what we are going to do third plot is a V DD plus V out, Now V DD plus V out that is the output voltage can dip to 0 according to our assumption and remaining time it is going to be V DD when its off its V DD. So, this is basically the waveform as for as V DD plus V out goes. Now, what are we interested in we are interested in finding out what is V amplitude of V out what can be the maximum amplitude of the out V DD that is the maximum amplitude of V out what is the current consumption of this circuit.

The current consumption of this circuit is equal to I bias 2 why because it conducting half the time not conducting the other half the time I mean during this time the current is perfectly equal to 0 when the current is 0 the power consumption is clearly going to be 0 and during the other portion of the time you have to work it out what the exact power consumption is as far as the voltage sources concern it is going to produce a voltage source of V DD it is going to deliver a current of I bias which probably means that the power consumption is V DD times I bias.

V dd times I bias is the power consumed, let us just keep it while I will show you it is not maximum amplitude of V out is V DD and if the amplitude is equal to V DD amplitude of the voltage across the R antenna is equal to V DD therefore, the power delivered to the antenna is V DD squared by 2 R and V DD by R is how much, when the amplitude is equal to V DD the amplitude of the RF current is equal to I bias which mean that V DD by that R is equal I bias. So, therefore, the power delivered V DD times I bias by 2. Now, if this is the situation then we are of course, wrong because we have got 100 percent of efficiency. So, that is why we are wrong.

The power delivered and the power consumed a specially is not correct the power consumed is not V DD times I bias by 2 let us take a look again. What is the power consumed? Power consumed is the power burnt by the MOSFET. So, power burning device plus the power deliver to the antenna; let us think about the power burnt by the MOSFET. So, look at the waveforms of current through the MOSFET and the voltage across drain and source, the product of these two averages over time.

Time of average of that will give you the power burnt in the MOSFET. So, it is basically integral 0 to T, 1 by T of that I bias plus I rf times V DD plus V out that is the power burnt by the MOSFET and you break it up you break up the product and what you are going to get is. So, first term is I bias times V dd plus the second term is I bias times of V out dt the third term is I rf times V dt and the forth term is I rf v out v dt now I bias times v out I bias is a constant. So, it is basically integral of v out dt v out is let say as for as the fundamental is concerned if you think of v out is sinusoid then the average v out is equal to 0 which means that this term is irrelevant as for as the fundamental is concerned we want to do the most approximate calculation over here and similarly I rf times v dd is also almost equal to 0 so as for as the fundamental is concerned is nothing.

So, we basically got two terms in this I bias and is V dd dt and I rf times v out dt how much is v bias mes v dd dt integral of that 0 to T is basically equal to T. So, the average is equal to I bias times v dd what about the second term integral 0 to T I rf times v out d t what is the amplitude of I rf is equal to V DD by RF amplitude of V out rather it is the I bias amplitude of V out is equal to another V DD. So, we have got two of these signal and 2 sinusoids the means squared value of that would be half of the product of the 2 amplitudes. So, therefore, what is the power consumed in the MOSFET. So, it is approximately 1.5 times I bias times V dd and what is the power going to the load.

Power going to the load is 0.5 times I bias times V dd and therefore, how much is the efficiency, we have run out time the something wrong over here we have to do this integral carefully and will evaluate the efficiency I am going to stop here what you are going to notice is that the efficiency of the class A is at max 50 percent. Efficiency of the class B is a little better, the class C is even better and so on. So, we are going to stop here and will carry this discussion forward in the next class.

Thank you.