Microwave Theory and Techniques
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Module - 09
Lecture - 44
Microwave Mixers - II: Circuits

Hello, welcome back. So, in the last lecture on Microwave Mixers, we studied mixer fundamentals, we covered the basic mixer operation, we saw what is the symbol and circuit representation of a mixer. And the mixer operation is basically if you have two frequency signals given at the mixture inputs, the mixer should produce the sum and the difference frequency outputs. And one of these outputs which chosen depending on the type of the mixture, which can be either up conversion or down conversion.

We see that the mixture is implemented using non-linearity basically and there are two types of mixer implementation; one is using non-linear device and another using a time variant system linear time variant system. And if we implement a mixer using physical devices, what we see at the mixer output, which is quite different than the ideal mixer output. And this mixer non-idealities are measured using various mixer performance metrics, which are conversion loss or gain. Then we have a port-to-port isolation, we have linearity, noise figure, spurious response and so on.

So, in this lecture, what we are going to do? We are going to start with the devices that we use for mixes, which are diodes and transistors. We will see how these devices basically provide mixing action and then we will switch to various mixer circuits, we will analyse the circuits, and try to understand how this circuits produce mixing actions, and how they can be used to implement a good performance mixer, let us begin.

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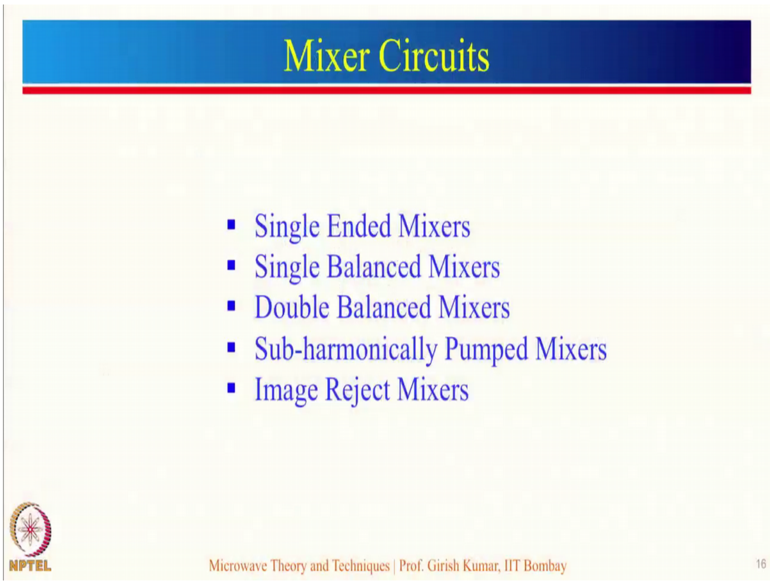

So, we are going to study different mixer circuits, which are single ended mixtures, single balanced mixers, double balanced mixers, sub-harmonically pumped mixers, and image reject mixers. And before going to these circuits, let us first understand the mixture devices that we use.

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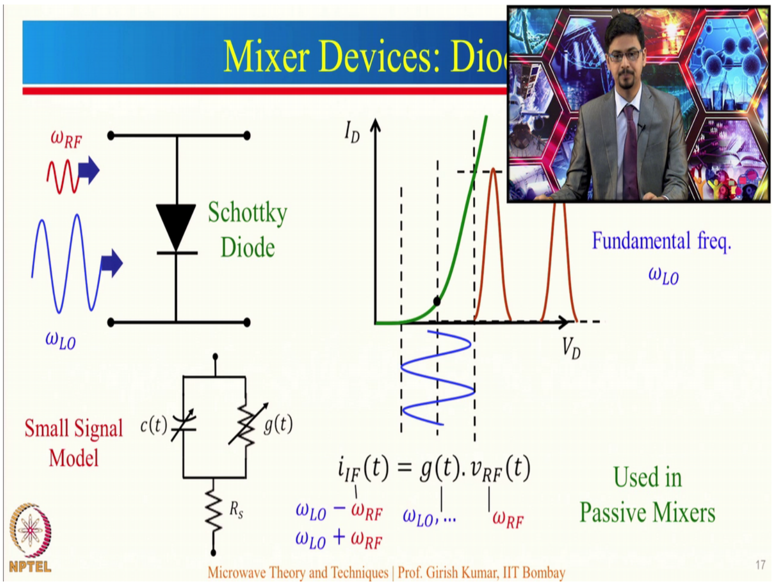

First is the diode. Unlike in most of the operations a PN junction diode is never used in mixing action, for the reason that the PN junction diodes have very long recombination carrier lifetimes, which is quite undesired for mixers, because mixers have to be switched very fast. So, the diodes has to be switched very fast. And for that, we need very low carrier recombination lifetime, which is given by the Schottky diodes, which are unipolar or majority carrier devices. So, in most of the mixtures, we use Schottky diodes, and we avoid PN junction diodes.

So, we have a diode connected in this fashion, and we know that the diode IV characteristic given by this non-linear or exponential curve. The black dot that you see here is the biasing point. And what first happens is to this diode we present the LO signal, which is one of the mixer input ports. We present the LO signal, this time varying LO signal which has quite large amplitude or a higher signal level. Drives the output current of the diode, it modulates the current by changing the diode junction voltage in this fashion. So, the current is left from a minimum value to a maximum value by the incoming LO signal. And this modulation of current actually gives rise to a modulation of conductance of the diode, because the diode conductance is nothing but the partial derivative of diode current with respect to the diode voltage.

So, g of t is equal to dou I D by dou V D. And since, V D is being changed in time by the LO signal, we get a time varying diode conductance, and the waveform looks like this. So, we have this time varying diode conductance waveform, which has fundamental frequency of omega LO. This is the basic of mixing action, that the LO signal which is a large amplitude signal causes one of the diode parameters to change in time. So, you have a time varying conductance, and the variation is add the LO frequency.

After this, we apply the RF signal which is of low level compared to the level of the LO signal, and because the RF signal is very small, we can apply the small signal model of the diode. And this model contains a time varying capacitance, which is the junction capacitance, a time varying conductance, and series resistance R s which accounts for the losses inside the diode. So, we understood that the conductance time variance is because of the time varying LO wave form that is applied across the diode. And this wave form actually also modulates the diode capacitance, but in the mixing action, the dominating effect is because of the conductance, so we have focused only on the conductance part.

Now, it is very simple, the IF output is given as the conductance into the input voltage. So, current is basically conductance into voltage. So, v RF multiplied with g of t to produce the IF current output. And this is basically what we want, we have two signals multiplying with each other, and these two signals are at different frequencies. So, v RF is at omega RF frequency, g of t has a fundamental frequency of omega LO. And hence, when we multiply these two signals at the output or the IF port, I should get the difference and the sum frequencies.

Now, of course, this waveform is not pure sinusoid, so it will contain additional frequency components along with omega LO. And hence, you will expect some spurious response in the output, which has to be filtered out. This is the basic of how a diode can produce mixing action, and because a diode cannot provide signal amplification, the diodes are mainly used in passive mixers. So, there are two types of mixers, depending on whether they provide signal amplification or not, one is a passive mixer, another one is an active mixer. So, if we use diodes, the mixture will be of passive type.

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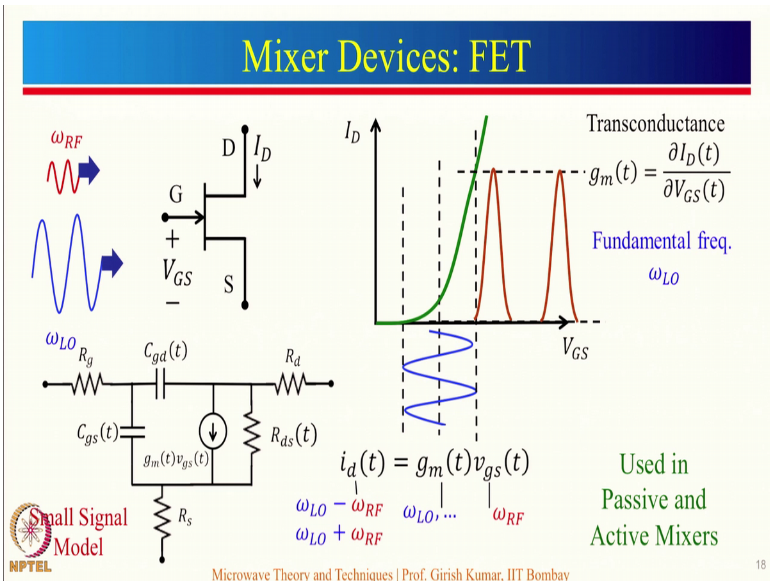

FET or field effect transistor is an another type of device that is used for mixing. The analysis very similar, so you have a gate, drain, and source terminals of a field effect transistor. The input signal is applied across the gate and the source, and the drain current is taken as the output. And we know that, the relation between I D drain current, and the V GS the voltage difference between the gate and the source, again varies exponentially, but this is the square law device, it does not contain a third order term.

And the same, we apply the LO signal at the V GS port. This LO signal modulates the drain current from a minimum value to a maximum value, and transconductance of the

FET, which is given by this expression. So, partial derivative of the drain current with respect to the voltage difference between gate and source is also modulated because of this LO signal. And the modulated waveform is like this. So, the time varying transconductance is the basic factor that causes the mixing. And this variation is at fundamental frequency of omega LO which is same as the LO frequency, which we are inputting at the mixture or the FET in this case.

After this, we apply a small signal RF, and because the signal level is very small compared to the LO signal. We can apply a small signal model of FET, which is quite involved compared to the diode model. So, we have R g, R d, R s, as the resistance is at all the three ports. We also have C gd, C gs, and R ds, which are also time varying. So, the time variation in these small signal parameters is also caused by the incoming LO signal. And the most dominant of all these is this g m into v g s or the g m which is the transconductance. And hence, the drain current is actually modulated by the LO signal.

So, the drain current is now given by the transconductance into the input voltage, which is v gs. So, now we are considering the small signal models. So, v gs contains only the RF frequency; g m we know that has fundamental frequency of omega LO; and the output current, because we are multiplying these two signals, should contain the difference and the sum of these two frequencies, which is the desired mixing action. The transconductance being a not pure sinusoidal, we will contain other frequency terms, and you will also have other frequency components present in the I D, which have to be filtered out using appropriate filtering actions.

So, this is how fundamentally a FET device produces mixing action, and because of FET or a transistor can provide signal amplification. FET can be used to implement passive as well as active mixers, which is the very important point. And all the active mixers are actually implemented using MOSFETs or BJTs these days. So, now we know that our diode and FET provide mixing action. Now, we will see how these components are actually added to give a complete mixer circuit.

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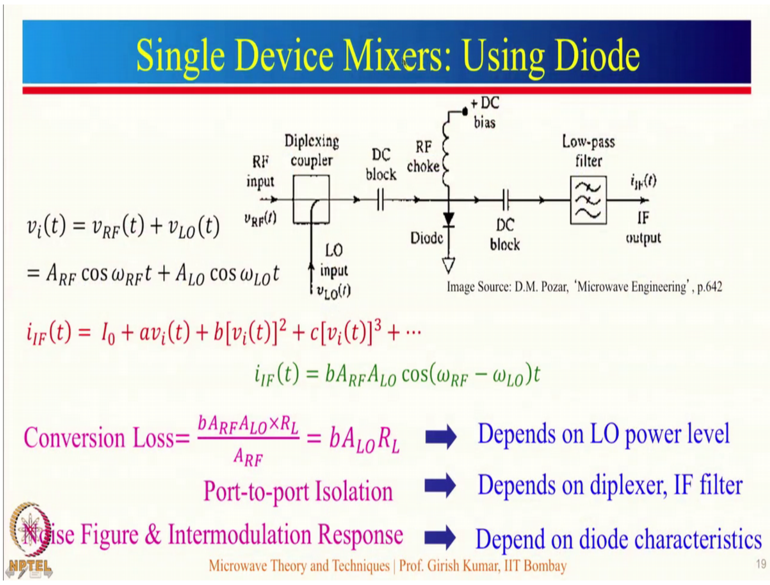

Let us take a simple case a simplest form, which is single device mixer or single ended mixer using a diode. Let us first analyse a circuit here. So, I have a diode here which causes the mixing, which is biased using an RF choke and a DC bias to avoid the DC signal to flow into the input and output high frequency ports. We have this DC block capacitors. The RF and LO signal are provided at the input of the diode, and they are separated using a diplexing coupler to provide the necessary isolation. At the output, the IF is taken after filtering either low pass or band pass.

So, the operation is quite simple we have v i input voltage at the diode input to be the sum of the RF and the LO voltage, which are nothing but sinusoids varying at omega RF and omega LO frequency. And using a non-linear equation, Taylor series expansion of the diode, we know that the IF current will have the DC part, linear dependency, square, cubic terms and so on. So, if I simplify this particular expression, the IF current output at the difference frequency will have this amplitude, so it will have b into A RF into A LO and the co sinusoidal term.

Thus the conversion loss of this mixture is nothing but the voltage at the IF port, to the voltage at the RF port, which is given as b A RF into A LO into R L. This is the current part, taken across a load resistor, and A RF is the input signal amplitude. So, if we take the ratio, we see that the conversion loss actually depends on A LO, which is the LO signal amplitude level, so it is very important factor. So, the conversion loss actually depends on the LO power level, as well as it depends on the diode parameters, but the LO power level dependency is very critical, you can have a good or a bad conversion loss or gain performance, if you choose the LO power optimally.

Port-to-port isolation in this case depends on this coupler over here. And for IF port, it depends on how good rejection this low pass filter provides. Noise figure and intermodulation response actually depends on the diode characteristics, which are inherent to these diodes. So, the diode selection plays a critical part to get the noise figure and intermodulation response. This is the simple circuit of diode mixer single device. And such a single device mixers can also be implemented using FET devices or transistors.

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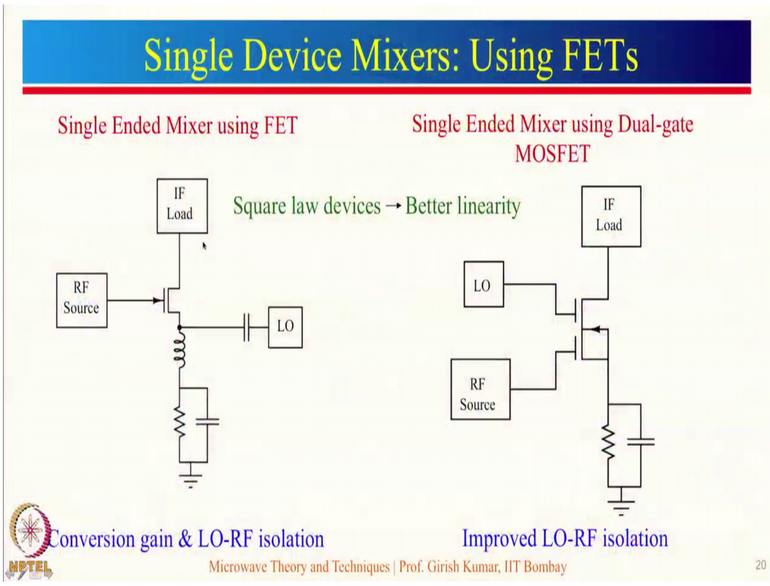

So, the major advantage FETs have over BJTs and diodes is that these are square law devices. So, they do not contain any cubic term in the output current expression, so they have a better linearity. Let us consider simple circuit using FET. We have an RF signal applied at the gate, LO signal applied at the source terminal, and the output is taken at the drain.

Now, the advantages; being a FET, it can provide a conversion gain, and because RF and LO are applied at two different ports of the FET, you have a good LO to RF isolation compared to the single diode mixers, which we just studied. And a better or improved LO to RF isolation can be achieved, if dual-gate MOS is used to implement a mixer using FETs. So, in this case, we have a dual-gate MOSFET, and the LO signal is given to one of the gate, and the RF signal is given to the other gate terminal. The output is taken at the drain, and you have stabilizing circuit over here. So, the advantage of FET mixers is that, they can provide gain, they can provide better LO to RF isolation, and they have better linearity.

Going forward, we are going to discuss balanced mixers and other types of mixer circuits. And to understand the circuit behaviour or to analyse the circuit, we will use diodes going forward, and we will avoid FETs. Similar circuits can be implemented using FETs with some modifications. Let us understand the next type of the mixture, which is single balanced mixer. The purpose of balancing action is to remove either the input signal or the LO signal from appearing into the output. We will see how this is achieved.

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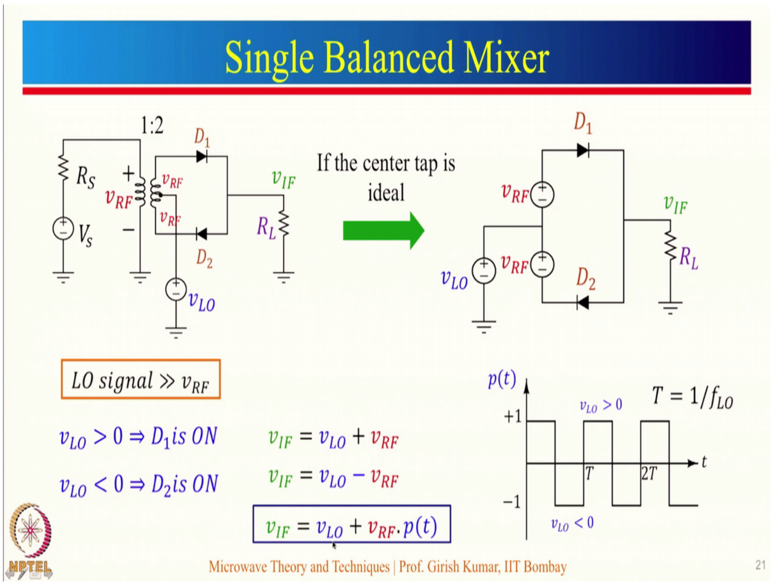

So, this is the typical circuit for a single balanced mixer. So, this is my RF input signal provided to a 1 is to 2 transformer. And we have a diode arrangement like this. So, this arrangement is very important, you cannot have any arbitrary arrangement of diodes, and still achieve balancing. So, if you have this particular configuration, I have to have this diode orientation appropriately.

So, I have this two diodes, which are connected in anti-parallel fashion. LO signal is given at the centre type of the transformer, and the IF signal is taken across a load. Now, before going to the circuit analysis, important thing LO signal is always very greater than the RF signal. And if you observe, the RF signal is actually provided out of phase for these two diodes. So, in the secondary of the transformer, you have RF as plus minus and plus minus, so both this RF signals appear across this diodes in out of phase manner, and that is why the RF currents actually circulate among these diodes, and we call this as a balancing action. And the RF currents do not appear in the output. We study this in detail further.

Let us say that the center tap is ideal. And in that case, this circuit can be reduced to this. So, we have a v LO, the v RF at the secondary of the transformer, these two diodes, and output voltage. Now, in case v LO is greater than 0, diode D 1 is on, and we get v LO, v RF, and v IF path. So, v IF is nothing but addition of v LO and V RF. When the v LO is less than 0, we get D 2 on, D 1 off, so the path is v LO, v RF and the IF signal. So, in this case, v IF is given as v LO minus v RF.

Mathematically, I can write it in this form. So, v IF which is the output voltage is equal to v LO plus v RF into p of t. Now, this p of t is nothing but a square wave, which ranges from plus 1 to minus 1. And the frequency at which this transition happens is nothing but the LO frequency. So, the output voltage is nothing but v LO plus v RF into p of t; p of t is given as this, its square wave transition between plus 1 and minus 1 with the frequency equal to the LO frequency or the local oscillator frequency.

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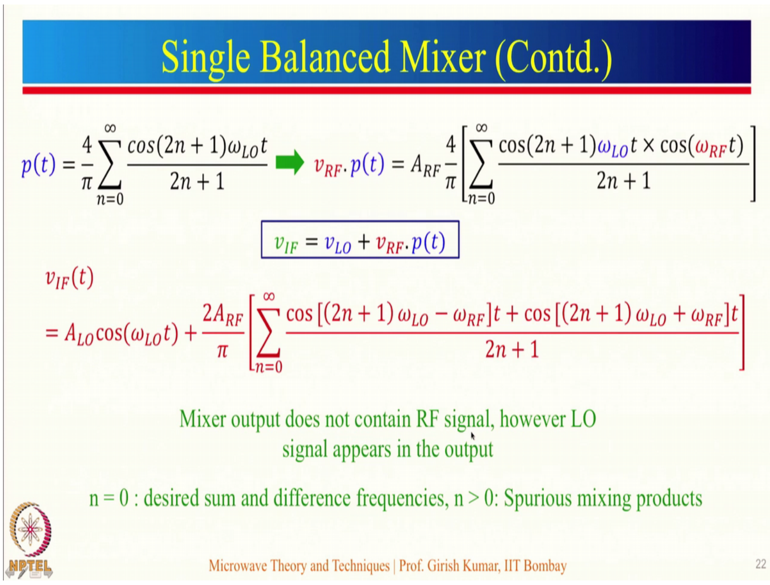

Now, the spurious analysis of p of t we know that, it is a square wave. So, it will contain the fundamental frequency omega LO, as well as all of it is odd harmonics. And if you simplify this equation by substituting the expression of p of t, what we get, is this. So, the v IF of t, which is the final output contains the omega LO term, which is the LO signal, it also contains mixing terms, which are given as here.

So, for n equal to 0, if you see, we get omega LO minus omega RF, and we get omega LO plus omega RF, which are the desired mixing outputs. However, we also get various other mixing terms, which are basically mixing of odd harmonics of LO with the RF frequency. So, at the output, we have just the LO signal, we do not have the RF signal, and we say that the RF signal is balanced out, but we also get various spurious signals, which are centred around odd harmonics of the LO. So, this is how a single balanced mixer fundamentally works. Next, we will see a practical single balanced mixer circuit, and we will again emphasis on the balancing action.

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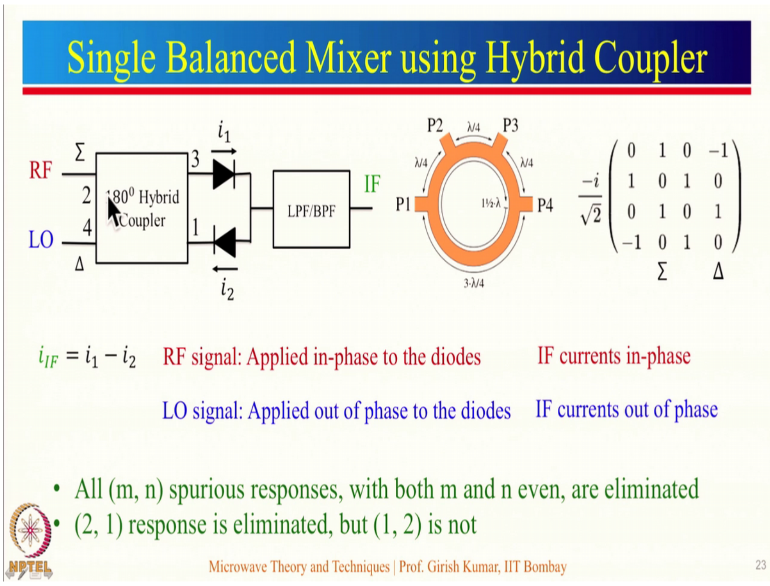

So, this is the circuit using 180 degree hybrid coupler and a diode arrangement. Again, the diode arrangement is anti-parallel, and the IF signal is taken after appropriate low pass or band pass filtering. So, RF signal is applied at the sum port of this 180 degree hybrid coupler, the LO signal is applied at the delta port of this 180 degree hybrid coupler, and we know that a 180 degree hybrid coupler is implemented using a (Refer Time: 18:56) as shown over here. So, we have ports 1, 2, 3, 4, we know that 1, 3, and 2, 4 are isolated from each other. In this case, 2 is the sum port, 4 is the delta port represented in here. So, this is this is the part, where the RF signal is applied. And this is the part, where the LO signal is applied.

Now, again remember the balancing action is one of the input signal is actually balanced out, the IF currents because of one of the signal just circulates around here, and it does not appear in the output. So, in this case, if you observe, the IF current is given as i 1 minus i 2. And the RF signal if you see is applied in phase to ports one and three, where the diodes are connected. So, for the both diodes, the RF signal is applied in phase. So, the IF currents produced at the output are also in phase because of the RF signal.

Now, for LO signal if you see here if I apply LO input at the delta port, at port one and three, the LO signal is actually appearing out of phase. So, for these two diodes, the LO signal appears out of phase. So, the IF currents that are produced because of the LO signal are also out of phase, and they are balanced out. So, another important observation in this circuit analysis is that, all the m, n, spurious responses with both m and n as even numbers are eliminated, which is the very important factor. So, we will have less spurious response. The 2, 1 term response is eliminated, but 1, 2 is not ok. So, this was single balanced mixers. The idea was you balance out one of the input signals, and you prevent it to appear in the output.

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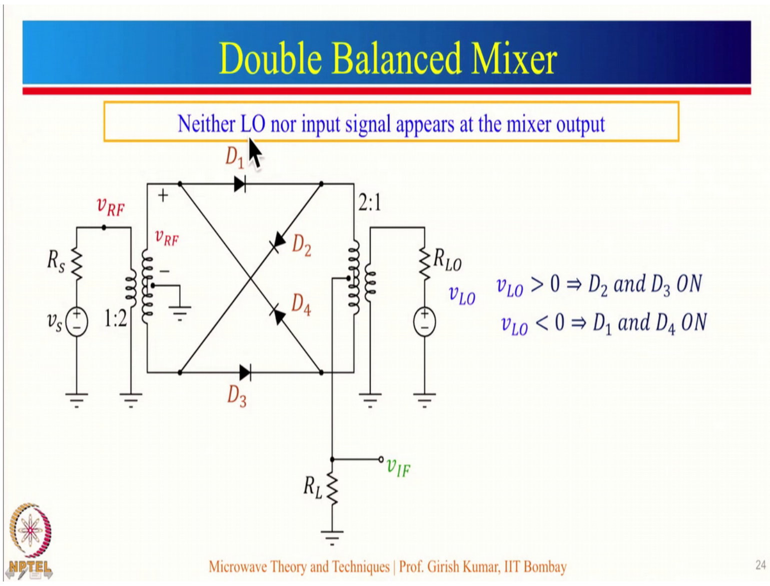

We see next, the double balanced mixers, where the idea is neither LO nor the input, which is the RF actually appear in the mixture output. So, simple in case of single balanced mixers for two of the diodes, one of the signal was applied out of phase. Here we have four diode arrangement. And for one diode pair, RF signal is applied out of phase. For another diode pair, the LO signal is applied out of phase. And this is how the balancing action will be performed. We will study this operation in detail. And we see that, when v LO is greater than 0, D 2 and D 3 will be on. And v LO is less than 0, D 1 and D 4 will be on. So, let us take both these cases and analyse further.

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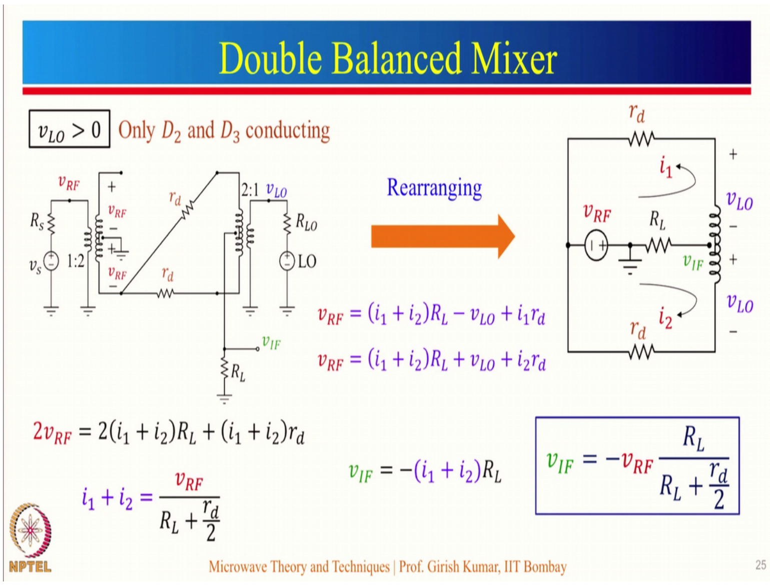

So, we have first case, v LO greater than 0, only D 2 and D 3 will be conducting. So, the circuit reduces to this, the diodes are replaced by equivalent resister r d. And if you rearrange this, we get circuit which is similar to this. Notice that, v IF which is the desired output voltage is nothing but the product of R L and the current flowing through it. So, the job is to determine what is the effective current that flows into this load register. So, we have a loop current i 1 flowing in the first loop, i 2 flowing in the second loop. And if you do the math, we solve for v RF in for both the loops, we get i 1 plus i 2 equal to v RF by R L plus r d by 2. So, v IF is nothing but minus v RF into R L divided by R L plus r d by 2. Notice the sign for the first case, when v LO is greater than 0, I get a minus sign.

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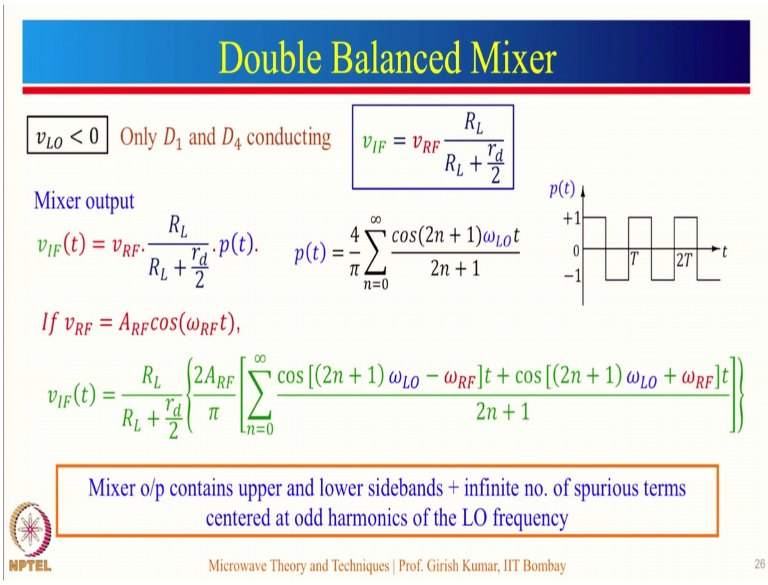

For v LO less than 0, D 1 and D 4 will conduct, we will do the similar analysis and what we get, is v IF equal to plus v RF into R L divided by R L plus r d by 2. So, there is a sign change. And as we have seen in the previous analysis, the output voltage will be given by this term v RF into a constant into p of t, where p of t is nothing but a square wave at a fundamental frequency equal to omega LO ranging from plus 1 to minus 1.

So, the output equation if you see here, it does not contain any of the input signals, it does not contain a signal with frequency omega RF, it does not also contain a signal with frequency omega LO. However, if you notice this expression for n equal to 0, you get the desired mixing, but for n not equal to 0, you have other spurious mixing products, which are nothing but centered at odd harmonics of the LO frequency. So, this is how a double balanced mixer works, it balances out both the input RF signal as well as the LO signal, and prevent it to appear in the mixer output. So, we have a better spurious rejection in case of balanced mixers.

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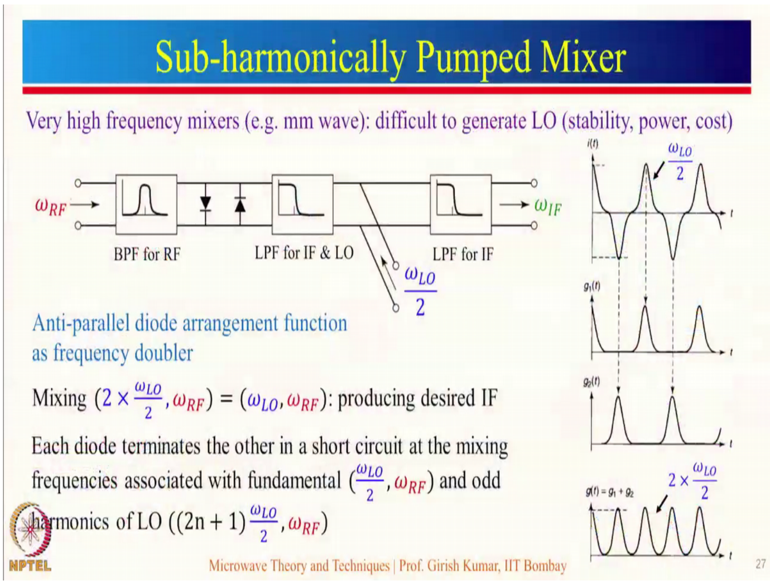

Next kind of mixture, we will see is a sub-harmonically pumped mixer. This mixture is mainly used, when a high frequency LO cannot be generated, so for applications such as millimetre wave mixers, it is very difficult to generate a local oscillator signal with good stability, the desired power level, which is high and reasonable cost. So, this is the circuit used for sub-harmonically pumped mixer. We have an omega RF, omega LO by 2. So, instead of having omega LO, we have the signal frequency, which is half the desired frequency. And this is the omega IF, which is the output.

The crux of this is the anti-parallel arrangement of the diodes as you can see here. And this diode arrangement as we can see, will give the desired mixing which is the mixing of omega RF and omega LO, even if we are supplying half the LO frequency. So, we have the necessary filters to filter out the respective signals. And we see we will see now, how this anti-parallel diode arrangement can function as a frequency doubler.

So, this is net current output. So, in one half the cycle of the LO diode D 1 conducts, in other half diode D 2 conducts, and since they are anti-parallel, the current directions are reversed. And this current variation happens at a frequency of omega LO by 2, which is the supplied frequency. Now, g 1 of t, which is the diode conductance for the first diode D 1 is this; g 2 of t is this. You observe that, both these conductance waveforms are out of phase with each other.

And hence, the net conductance which is sum of these two conductance waveforms is like this, and which is at twice the supplied frequency at the LO. So, the net frequency with which g of t varies is nothing but omega LO, even though the supplied frequency is half of omega LO. And this is how the mixing of omega RF and omega LO is achieved, and you get the desired IF signal.

You might wonder what happens to the mixing of omega LO by 2 and omega RF. So, this fundamental mixing is avoided to appear in the output, because one of the diode acts as a short circuit for this mixing, and also for mixing with all the odd harmonics of omega LO by 2. So, with this arrangement, only the mixing products arising because of omega RF and omega LO will appear at the output, and others will be terminated or they circulate around here. So, this is how sub-harmonically pumped mixers works. Next, we will see an important mixer type, which is called as image reject mixer.

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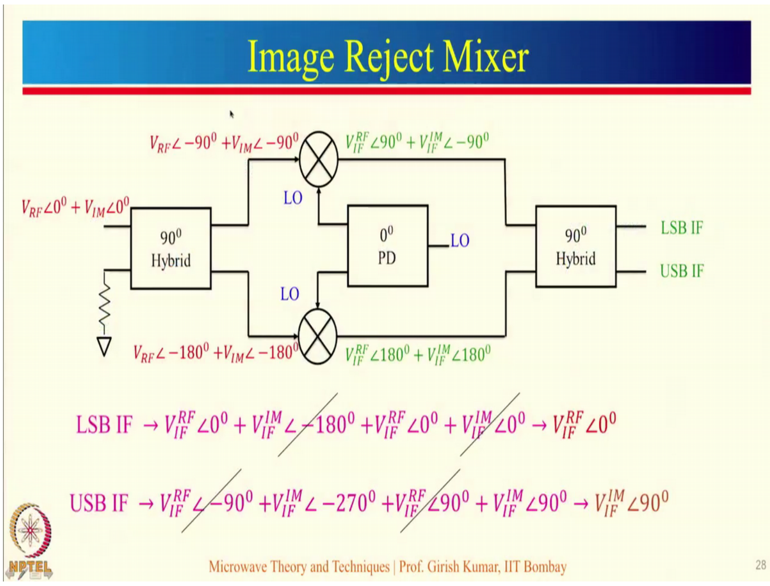

And this is the circuit that we are using for image reject mixers. So, we have two hybrids 90 degree hybrids; one is the RF 90 degree hybrid, another is the IF 90 degree hybrid. We have two separate mixtures. And the LO is given using a 0 degree power divider. So, basically the LO given to both these mixtures are in phase. Now, let us consider what happens, when we have an image signal along with the desired RF signal at the input. When this signal passes through the hybrid at this point, both this signals will be shifted by 90 degree in phase. So, RF and IM both have phase shift of minus 90 degree; at this point, both will have a phase shift of minus 180 degree.

When the mixing action happens, so this is v RF is at minus 90 degree phase, LO is as 0 degree phase, if a mixing between these two happen, the IF generated because of that mixing. So, IF generated because of the RF signal is at a phase of 90 degree. Whereas, when the IM signal which is at minus 90 degree mixes with the LO signal which is as 0 degree phase, when they mix, the IF generated due to the image frequency is at minus 90 degree phase. Similarly, at this end the LO signal at o phase mixes with the RF signal which is at minus 180 degree phase, and it produces the IF with a 180 degree phase output. LO signal mixes with the image signal, and it also produces the IF output with a 180 degree phase.

So, remember that, the phase difference is observed at this particular point at the mixer output, whereas the IF output because of RF and IM, which is the image are at the same phase. Now, these two signals when applied at the input of a 90 degree IF hybrid, let us see what happens. So, the IF hybrid have two outputs, one is the LSB IF output, one is the USB IF output. So, at this particular point we will see that, this signal will further be shifted by 90 degree. So, we have 90 minus 90 which is 0; we have minus 90 minus 90 which is minus 180. At this point from this particular input signal, we have a 180 degree phase shift. So, we will have 180 minus 180 which is 0; we will have 180 minus 180 which is again 0.

Now, if you see IF components because of the RF, this one and this one, they are in phase, the IF components because of the image, they are out of phase, so they will cancel out. And at this particular port, you will get the IF component only because of the RF signal. Similarly, in the USB IF, the RF parts get cancel out, and the IF output because of the image retain. So, at USB IF port, you will get an IF signal only because of the image signal. So, this is how resulting IF components because of the RF, and image are separated out using an image reject mixers.

So, we have studied various types of mixers circuits in this particular lecture, let us review. So, first we considered a diode, how it performs as a mixture, how a FET fundamentally gives mixing action, then we studied single diode mixers using FETs as well as diodes, then we studied single balanced mixers, we studied double balanced mixers, we studied sub-harmonically pumped mixers, and finally we studied image reject mixers. So, these are the main types of mixer configurations that are used. And in the next lecture, we will see how this different mixer circuits in compared to each other perform for various performance metrics that we discussed in the first lecture. We will see the comparison, and based on that, we will see how the design aspects have to be consider while designing a mixer.

Thank you.