Microwave Theory and Techniques
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Module - 9
Lecture - 43
Microwave Mixers – I:
Fundamentals

Hello, my name is Vinay Narayane; I am pursuing my Ph.D., studies under the supervision of Prof. Girish Kumar. And the topic of today's discussion is Microwave Mixers. Microwave mixers are mixers in general is a very vital component in the RX and TX, which is a receiver and transmitter chain of any communication system. So, be it GSM, be it mobile communication, be it satellite communication, mixers are very vital components. So, we are going to study these mixers in the upcoming slides and in this lecture henceforth. So, let us begin.

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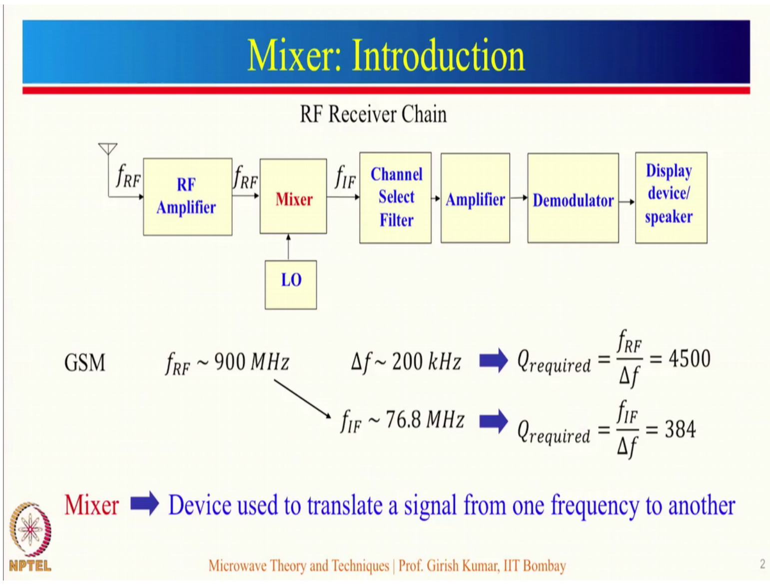

Let us take an example of an RF receiver chain, where we have an antenna, which receives the signal. And we have an RF amplifier, which amplifies the signal, then we have a channel select filter, and the signal is further processed using amplifier, demodulator, and then finally given to a display or a speaker. Now, let us take a case of a GSM mobile system, where the incoming signal is at a frequency of 900 megahertz. And the channel select filter requires a bandwidth of 200 kilohertz.

Now, to achieve this bandwidth at this particular frequency, we require a Q of about 4500, which is like very very big, and impossible to achieve at such a higher frequency. If now we convert this incoming signal of 900 to lower frequency value or an intermediate frequency value, let us say of 76.8 megahertz, we get a Q requirement of the filter to be 384, which is still high, but can be accomplished or can be achieved, and it is low compared to the 4500 value in earlier case.

So, the point here is it is difficult to process, the signal at very high frequency. And hence, we have to convert this high frequency signal into a lower frequency value. And that is why, we need a block in between the RF amplifier and the channel select filter, and that block is nothing but mixer. So, mixer is nothing but a frequency translation device, which translates a frequency from one value to another or it translates a signal from one frequency to another. This is the fundamental operation and need of a mixer.

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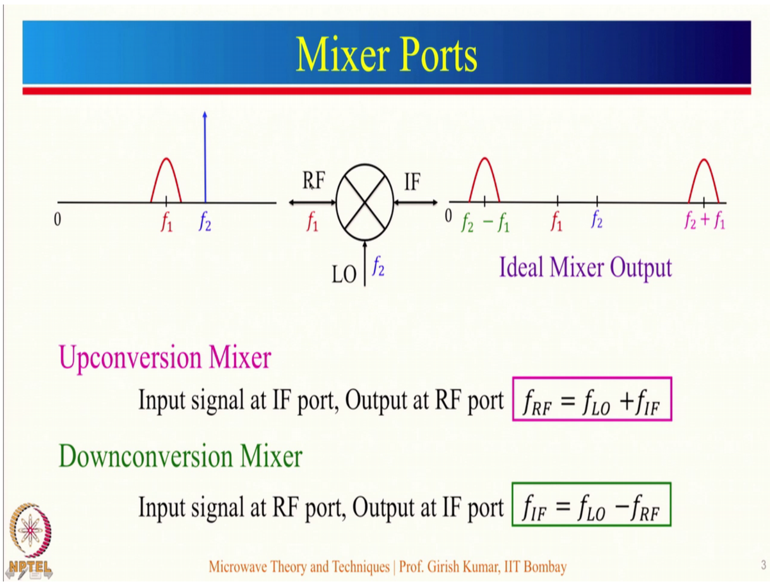

We are going to study mixers in three parts. In first part, we will study the fundamentals of a mixer, we will study mixer as a circuit component, what are the input, output signals. And in the second part, we are going to study the devices and circuits, which are commonly used to implement a mixer. In the third part, we are going to study some of the design considerations using an example.

Let us begin. So, mixer has three ports. You have an RF port, and LO port, and an IF port. RF stands for Radio Frequency, LO is the Local Oscillator, IF is Intermediate

Frequency. RF and LO are typically high frequency ports, whereas IF is low or intermediate frequency port. The RF port and IF port can be used both as input and output ports depending on the application, while the LO port is always the input port.

Now, let us see a basic operation of a mixer. If we have two frequencies at the input of the mixer f 1 and f 2, which are given in the spectral from here, so we have a f 1 signal, which is a band limited signal. And we have local oscillator, which is at a frequency f 2, then the mixer output is like this. So, ideally with 2 frequencies input, the mixer produces the sum and the difference frequency. So, at the mixer output, we should get f 2 plus f 1, and f 2 minus f 1 ideally. So, depending on the application, we either choose one of this sideband. So, this is called as the lower sideband, and this is called as the upper sideband.

So, there are two kinds of mixer depending on which frequency signal that we choose at the output, and they are upconversion mixer and downconversion mixer. In case of upconversion mixer, the input signal is given at the IF port. The signal at the IF port mixes with the signal at the LO port, and these mixing signals produce the sum and the difference frequencies. And in this case, we choose the sum frequency, which is the RF frequency. So, f RF is equal to f LO plus f IF.

In case of downconversion mixer, the input is at the RF port, and the signal at the input RF port mixes with the signal at the LO. And these two signals after mixing with each other produces the sum and the difference frequency, and we choose the difference frequency in this case, which is output at the IF port. So, f IF is equal to f LO minus f RF. This is the basic operation of a mixer in upconversion and downconversion case.

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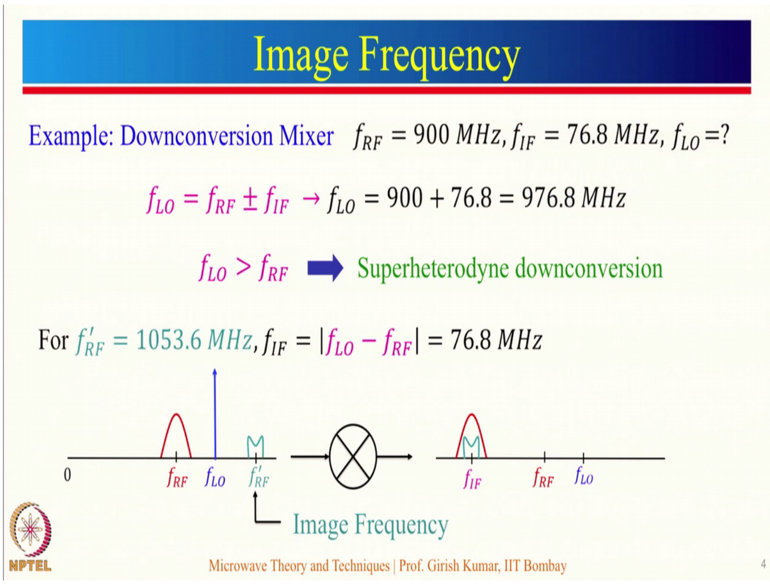

Now, let us take an example of a downconversion mixer. Let us say that, we have an incoming frequency at the RF band, which is equal to 900 megahertz. And the IF desired is 76.8 megahertz. And the question is the LO frequency that is required to produce this conversion. Simple, we have a formula f LO is equal to f RF plus or minus f IF using the basic mixer operation. Now, if I choose the plus sign here, I get the local oscillator frequency to be 900 plus 76.8, which is equal to 976.8 megahertz.

Since, I have chosen the plus sign, and the local oscillator frequency is higher than the incoming RF frequency such kind of downconversion is called as superheterodyne downconversion. We must have known this or heard this term quite a bit of time. And the super in this case, indicate that the local oscillator frequency is greater than the RF frequency. Let us take an interesting case here. Now, in the RF at the input of the mixer, we have an another frequency, which is at 1053.6 megahertz. This frequency along with the desired RF, which is at 900 megahertz, mixes with the LO frequency, which is 976.8 megahertz and the mixing between this frequency and this frequency, if you see the produces the same IF output.

In the frequency domain, if you see the spectrum, you have the local oscillator at this frequency, you have the desired RF band. And this is the special frequency that we are talking about, and after conversion both this signals mix with the LO, and they produce the same IF output. So, basically if you see this kind of operation is really not desired, this is a mixing or scrambling of the desired signal and should be avoided. So, this frequency is called as the image frequency. And it has to be removed.

There are ways to remove this image frequency or to nullify the effect. And it can be achieved using two ways, one is you can have a image reject filter in the RF path, so that you do not allow this frequency to come into the mixer. And second is you use an image reject mixer, which is the configuration that we will discuss in later part of this course. So, image frequency is very important, it has to be considered and should be avoided to enter the mixer.

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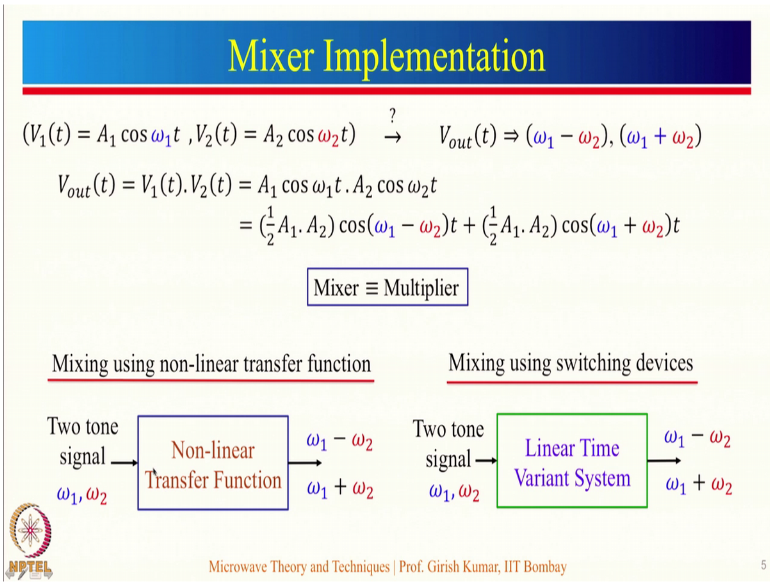

Now, the question is how is this implemented the basic operation. So, we have two signals with frequency omega 1 and omega 2 a sinusoidally varying signals. And the question is what operation do I perform on this signals to get the output signal, which contains the sum and the difference frequency, so it is simple. If we just multiply these two incoming signals that is a multiply A 1 cos omega 1 t into A 2 cos omega 2 t by using basics trigonometric relations, we get an output, which contains the difference and the sum component of the frequencies.

So, mixer is inherently or basically is a multiplier. And that is why, in the symbol of the mixer if you have noticed; we represent it using a multiplication symbol ok. So, how is this multiplication achieved in real world, what devices or what techniques, we use to achieve the multiplication physically. So, there are two techniques. In first, we use a non-linear transfer function system, and in the second we use a switching device, which is nothing but a linear time variant system.

So, in the first case, we have a system, which has a non-linear transfer function. And at the input of this system, if I give two tone signal, a tone meaning of frequency. If I have a two tone signal input to this particular non-linear system, I get at the output the difference and the sum frequencies. Similarly, in case of switching devices if I have a linear time variant system, and at the input of this system, if I have two tone signal with two different frequencies. At the output, I can get the difference and the sum frequencies. So, these are the two techniques, which are used to analyze the operation of a mixer and to implement mixers. So, inherently these two techniques are the same, but just the way of analysis is different; although, we study both these techniques in detail in upcoming slides.

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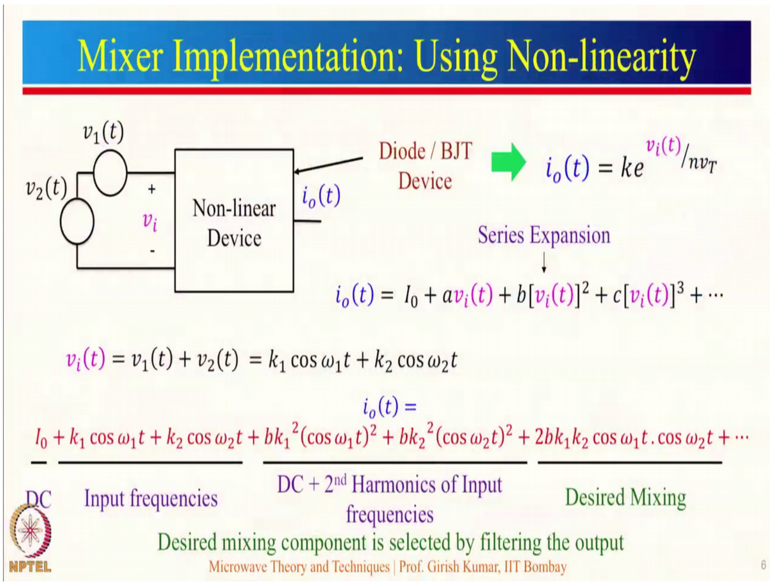

So, let us take the case of mixer implementation using non-linearity. So, here you can see, we have a non-linear device. And we know that, it can be a diode or BJT, at the input we have a signal v i and the output we have a current, which is i o. Now, we know that the diode current and voltage relation. So, the output current varies exponentially with the input voltage. And if I expand this particular expression using a Taylor series, what I get is this expression.

If you observe, the output current here depends not only linearly on the input, but also it contains the square of the input, the cube of the input and so on. So, this is the non-linearity, which we required to achieve the mixing action. Now, the v i is nothing but sum of two input signals v 1 of t, v 2 of t, which are at two different frequencies omega 1 and omega 2. If I substitute this expression into this particular equation, and I solve it, analyze it, I get the following terms. Now, this particular expression that is being written here is taken by considering only the 2nd order term. The 3rd order term is not considered in this particular expression, but you can always solve it. And see: what are the frequency terms, which are generated because of the cubic term ok.

So, let us analyze this output in terms of frequencies that it contains. So, first you have an I 0, which is the DC component, you have the input frequencies, you also have the second harmonics of this input frequencies along with the DC signal, and you have the desired mixing, which is omega 1 t into omega 2. So, cos of omega 1 t into cos of omega 2 t, which will in turn produce omega 1 minus omega 2 and omega 1 plus omega 2. So, the desired mixing component is of course, should be chosen by using appropriate filtering. So, you see that by using a non-linear device in actual you get a lot of different frequency components at the output of a mixer along with the desired output. So, this is how a mixer is implemented using a non-linear transfer function device.

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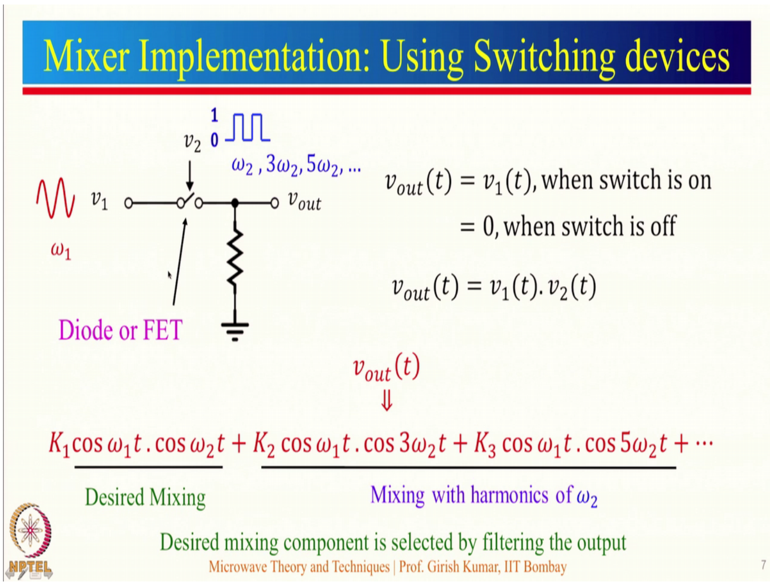

Let us take the 2nd case, where we have mixer implementation using a switching device. So, in this case, you have a input sinusoidal signal v 1, which is given to the output through a switch, which is controlled by the second signal v 2, which is typically a square wave ranging from 0 to 1. So, the input is switched to the output using a control signal v 2. So, simply v out is nothing but v 1, when the switch is on. And it is equal to 0, when the switch is off.

Mathematically, we can write it as v out is equal to v 1 of t into v 2 of t. This is because the switch on condition is achieved when the v 2 is 1, and switch off condition is achieved when v 2 is 0. So, v out is equal to v 1 of t into v 2 of t. And if these two signals are at two different frequencies, we achieve what we desire, which is the mixing. So, if v 1 is at omega 1, v 2 is at omega 2, I multiply these two signals, and at the output I should get v out, it containing the desired mixing.

But, there is a discrepancy that this is a square wave, and it cannot contain just the omega two term here, just a single frequency, it has to contain the odd harmonics of this frequency as well. So, in conclusion in the v out, we contain the desired mixing, which is cos omega 1 t into cos omega 2 t along with the harmonic mixing, which is omega 1 mixing with thrice omega 2 omega 1 mixing with 5 omega 2 and so on. And of course, you have to filter, the desired mixing signal using appropriate filtering. So, the switch, which we mention here or the switch that we discussed here can be implemented using a diode or FET or any kind of transistor.

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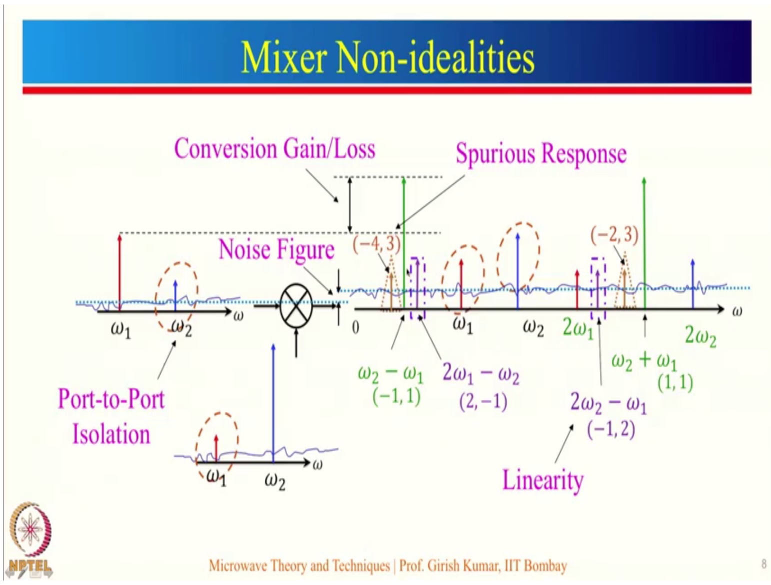

So, let us review the basic mixer operation again, we have a mixer, we have a mixer here at the input RF port, I have a signal at omega 1. At the LO input local oscillator input, I have a signal at omega 2. And the corrugated line that you see here is nothing but the noise floor present at both this inputs. And ideally the mixer should produce the sum and the difference of these two frequencies, but as we just saw, when we implement a mixer using various physical devices. The mixer output contains lot more than desired or there are various undesired products that are present at the mixer output.

So, let us see when I turn on this mixer, what are the frequencies and components that are produced at the mixer output. So, this is what happens, when the mixer is turned on the desired signals, where just omega 2 minus omega 1 and omega 2 plus omega 1, but you see that there is a lot of changes that have happened in this process. Now, take a moment, you can pause the video and observe what has happened. So, I will I will just flash it again. So, you have a mixer you have two signals, and ideally you should produce the sum and the difference, but this is what happens, when you turn on the mixer.

Now, note down the observations, what are the things that have changed, when the mixer was turned on, and you will notice several things, which are called as mixer non-idealities. And these mixer non-idealities have to measure using some parameters; this parameters are called as mixer performance metrics or mixer specifications. So, let us go one by one. First observation, you have an input RF signal at some level, but the output

IF is at a certain different amplitude level. And this difference is called as the conversion gain or loss.

So, in this particular case, I have shown an amplification. So, you have a conversion gain, but in some cases, you can also have a conversion loss. So, this is one of the important specification of a mixer. Of course, it is not an non-ideality, but it is a specification that a mixer has. It is a performance metrics that should be specified, when you mention about a mixer.

Second thing, if you have noticed, there are certain things, which are appearing at the input ports as well. So, after the mixer was turned on, I get the omega 2, which is local oscillator frequency coming at the RF frequency at the and the RF frequency coming at the LO port, and also I have omega 1, omega 2 at the IF output. So, these are called as port leakages or signal leaking from one port to another. And the mixer specification or mixer performance metrics related to this is called as port-to-port isolation. So, it is very important that these leakages should be minimized to a level as low as possible.

The third thing that you might have noticed is the noise floor, if you see the noise floor level here. And if you see the noise floor level at the output, it is certainly raised right. So, the mixer is adding certain amount of noise in the process. And this noise addition is measured using a noise figure metric, which is familiar to us, we know: what is the noise figure, mixer being a non-linear device also has a noise figure associated with it.

Next, we observed, there are various terms. For example, twice omega 1 minus omega 2 twice omega 2 plus sorry twice omega 2 minus omega 1 and the coding here, if you have noticed is nothing but I, the first number represents the multiplication of omega 1. The second number represents the multiplication of omega 2. So, it is like one integer multiplier here, second integer multiplier here. So, this is minus 1, 1; this frequency component is 2 minus 1; this component is minus 1, 2; this component is 1, 1 and so on.

So, this is the coding, which we will see later, how a general mixer equation is represented, and these signals are again not desired. These unwanted signals arise because of the non-linearity present in the mixing device, and these are called as intermodulation products. And this nonlinearity is measured using a performance metrics called as linearity. So, we say a mixer is more linear, if these frequency components generated at the mixer output are very low compared to the IF output. So, linearity is a very very important factor or very very important performance metrics while specifying a mixer.

Next, we see this minus 4, 3; minus 2, 3 components, which are arising in the mixer output, and these are called as spurious responses. These arise, because a multiple harmonics of the incoming signal, which is RF signal and harmonic of LO signal mixed with each other. And they produce something, which is not desired. Now, you might wonder that, we are anyway filtering the output. So, all this things can be filtered out, but the thing to be worried here is this. If you observe, the intermodulation product arising because of the non-linearity and because of the spurious response are very close to the desired IF output. So, even if I put a filter over here, I cannot reduce these particular components beyond a certain level, and they might cause if output to be degraded. So, let us see all this specifications one by one in detail in upcoming slides.

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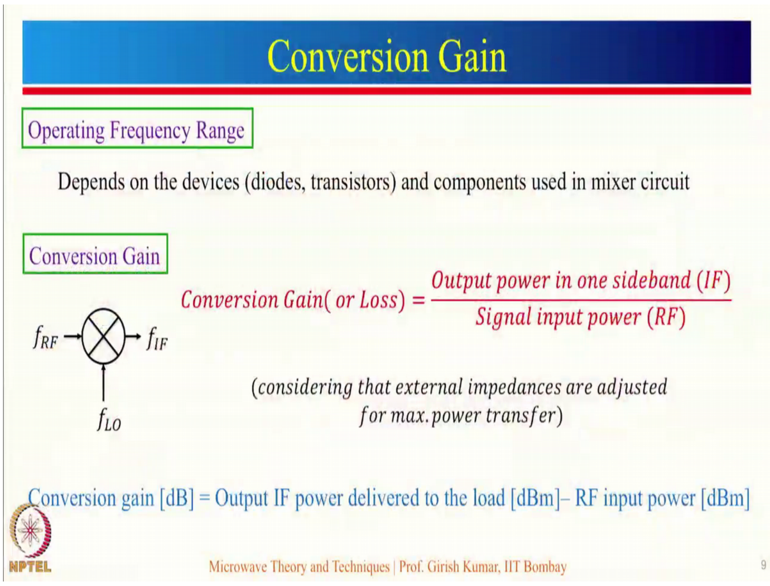

So, before going to the conversion gain, let us first discuss about the operating frequency range of a mixer. And it depends on the devices, which are nothing but diodes and transistors that are used while building the mixer, and also depends on other components that have been used to build the mixer circuit. Conversion gain very simple, it is defined as the output power in one of the sidebands, which is the IF output power divided by the RF input power.

In dB, it is simply the difference between the IF power and the RF power in dBm. Now, while defining conversion gain using this expression, we have assumed that the matching has been taken care of. So, this expression does not account for any mismatch losses, buts in literature you might see that the conversion gain expression or conversion gain number also includes the mismatch losses ok. Next is the port-to-port isolation.

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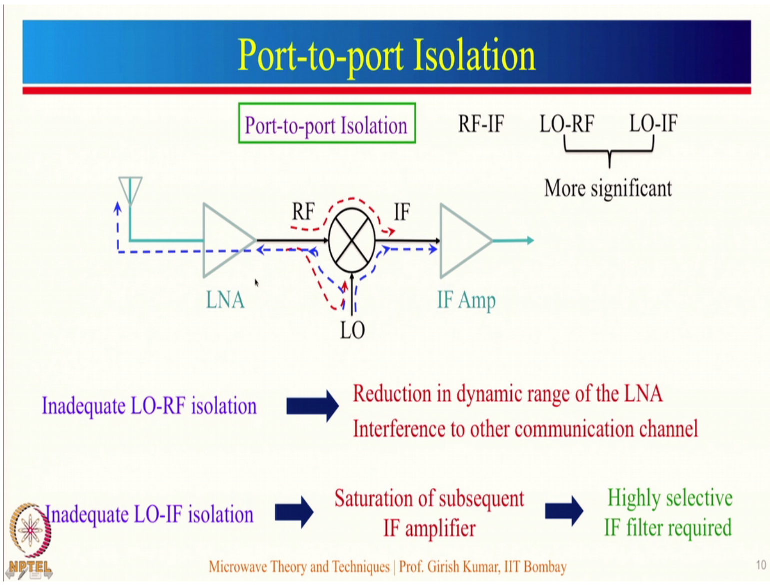

We have signal leaking from the LO port to the RF and IF port. We have signal leaking from the RF port to the LO and IF port and so on. So, the important one are the LO-RF and LO-IF isolations, which are more significant. And we will see that, why these are more significant as compared to RF-IF isolation. So, let us first consider the case that you have inadequate LO to RF isolation, which means that a considerable amount of signal from the LO port leaks into the RF port. And one thing that I want to mention, which we will see later is that the LO signal has a higher amplitude than the RF signal.

Now, before the mixer, we have an LNA and an antenna connected to it. So, let us say that the LO signal leaks into the LNA output, and this will result in a poor dynamic range of the LNA. So, this will reduce the dynamic range of the LNA. And the if LNA has a non-zero s 1 two value, the signal will further go to the antenna, and this will cause interference to other communication channels. In worst case, in case of defense application this leakage of LO signal through antenna might enable your enemy to locate your receiver.

Let us take a case of inadequate LO to IF isolation, where a considerable amount of LO power leaks into IF port. And after the mixer, after the IF port, we typically have an IF amplifier. And if the signal leaks into the IF amplifier, it might end up saturating this amplifier. And hence, you might require a very sharp filter to reject the LO leakage going into the IF amplifier. So, these are the things, which have to be considered, and it is very important to have a good port-to-port isolation numbers for a mixer.

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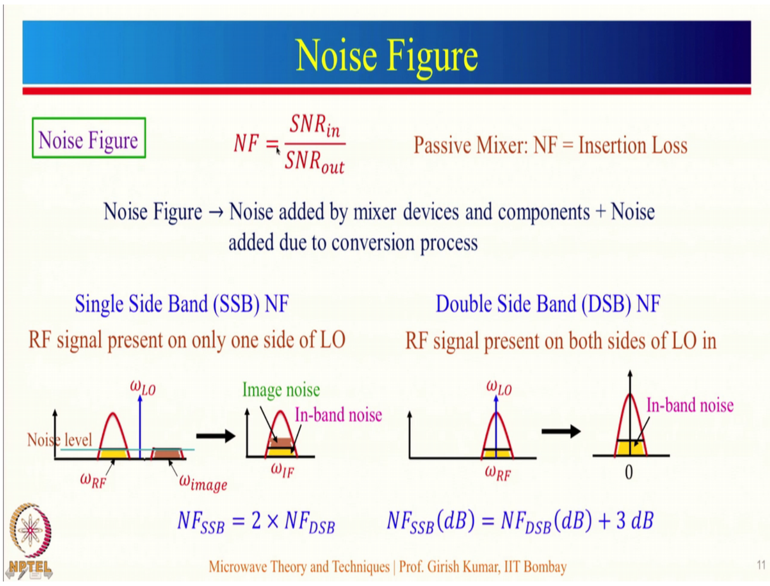

We have a noise figure to be considered for a mixer. We know that noise figure is defined as SNR in by SNR out, and the noise figure basically tells you, how much noise is being added by the mixer to the input signal. So, the noise added not only depends on the mixer devices and components, but it also arises because of the conversion process. And we will study this using a simple example. So, there are two types of noise figure specification. One is an SSB, which is single sideband noise figure. Other is a DSB, which is double sideband noise figure.

So, in case of SSB as you can see here. The RF signal, which is the band limited signal is present only on one side of the LO. So, this image noise, which is present at this particular frequency folds back, after the conversion onto the same IF output. So, as you can see here, you have a in-band noise plus on top of it, you have a image noise setting, after the conversion process whereas, in case of double sideband mixers, where you have the local oscillator frequency and the RF is present on both sides of this frequency. After mixing conversion, you do not have the image noise addition. It is just the in-band noise that is present with the mixer output. And hence, we see that the SSB noise figure is twice that of the DSB noise figure or SSB noise figure is 3 dB higher than the DSB noise figure. This is the very important point to be considered while discussing mixer noise figures.

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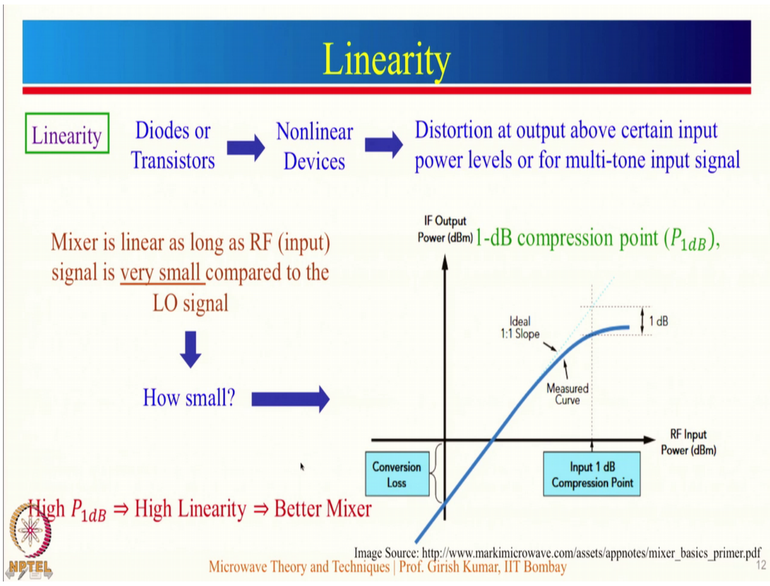

Next, we will see linearity; very important although a mixer is implemented using a non-linear device the mixer has to perform linearly, which means that the output signal has to change linearly with the changes in the input signal. And this will happen as long as the input signal is very small compared to the LO signal. But, the question is how small, and how small is measured using two specifications, one is 1-db compression point and another is IP3 point, which is called as 3rd order intercept, we will see this later.

First we will see: what is a 1-dB compression point. So, let us focus on this graph, we have an IF output on the y axis, and we have an RF input power on the x axis. As I increase the RF input power, IF output power also increases linearly only up to a certain point of RF input level. So, after this point if I keep increasing my RF input power my IF output power starts saturating, it does not vary linearly. And the value of the input RF signal level at which the difference between the actual IF power and the desired IF power is 1-db is called as the input 1-db compression point. So, this is a very important specification higher is this point, better is the linearity, better is the mixer.

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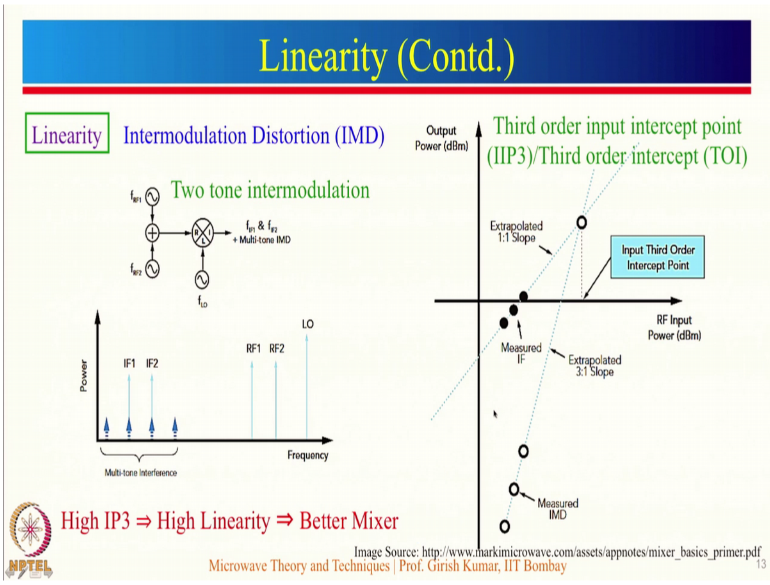

Next, we will see the intermodulation distortion, which is measured using IP3 point. So, the system is you have a mixer at the input, you give two tone equal amplitude signal represented like this here, RF 1, RF 2, and you have local oscillator. And what happens is these two signals mix with the LO to produce the desired outputs along with certain spurious signals. So, this level of spurious signals become equal to the desired output at a certain input power level of these two signals, which is explained using this graph.

Let us say, you have an output power on the y axis and you have an RF input power on the x axis. This is the desired IF output, which is this. And you see this line, which has a slope thrice that of this line is nothing but the graph of these intermodulation products. So, the point or the input power level at which these two signals have equal amplitude is called as input third order intercept point or IIP3. Now, this point is a is not an actual point, it cannot be measured instead what we do is, we measure the linear output If output, we measure the three points on the IMD, which is intermodulation distortion. We extrapolate these two lines and we see that the intersection is given by the IP3 point. It is very important specification higher is the IP3 point, better is the mixer.

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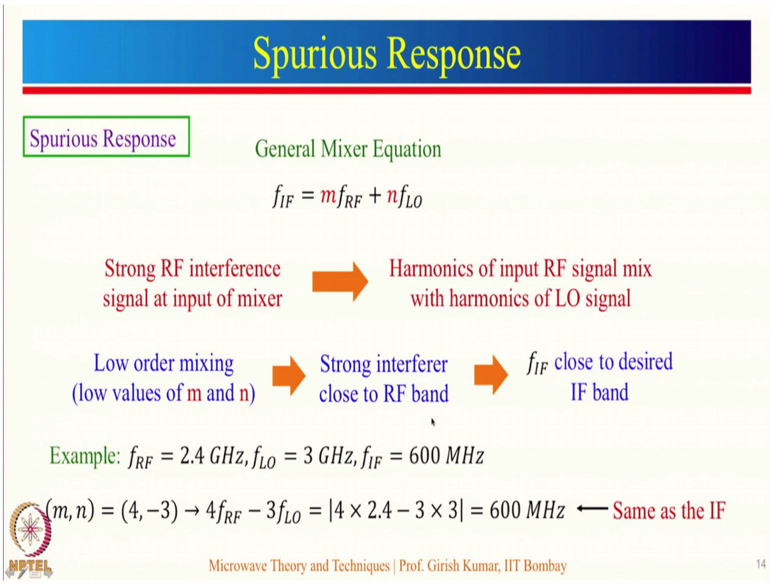

And lastly, we will consider the spurious response. So, a mixer general equation is given as this. So, you have IF output arises due to mf RF plus nf LO, where m and n are integers, they can take positive as well as negative values. And this becomes important, because let us say normally we have m equal to 1 or minus 1, and n equal to 1 or minus 1. But, if you have a strong RF interference signal at the input of the mixer, it might happen that the higher harmonics of this RF signal might mix with the harmonics of the LO. And the mixing product of these two undesired signals can fall into the IF frequency band, which is again interference and should be avoided.

So, let us take an example. So, you have a f RF of 2.4 gigahertz, you have f LO of 3 gigahertz, and the desired IF 600 megahertz. And now, you predict m and n as 4 and minus 3, you have 4f RF minus 3f LO you get a signal, which is exactly equal to the IF frequency, which is totally not desired, because it overlaps with the desired signal, which is produced by the input of 2.4 gigahertz (Refer Time: 29: 41) very important to have very good spurious response in a sense that the spurious products that have generated are very low compared to the desired IF output.

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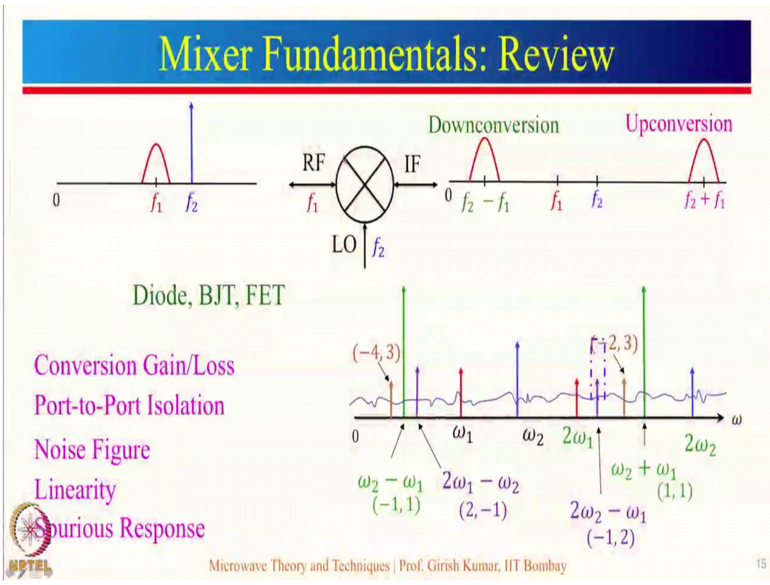

So, let us review the mixer fundamentals that we have discussed so far in this lecture. So, a mixer is represented using this symbol. It has three ports RF, LO, and IF. And the basic mixer operation is if I have two frequencies at the RF and LO, f 1 and f 2, ideally I get f 2 plus f 1 and f 2 minus f 1. If I choose the sum frequency, it is called as upconversion process or upconversion mixer. If I choose the difference frequency, the process is called as downconversion or a downconversion mixer.

The mixer can be implemented using a diode, BJT, FET as a non-linear device or as a switching device. And if we implement the mixer using these things, what we actually get, so is this is the ideal output what we actually get is this. And these are the mixer non-idealities or specifications or mixer performance matrix, which are nothing but conversion gain, port-to-port isolation, noise figure, linearity, and spurious response. So, these are the things that we discussed in this lecture.

In next lecture, we are going to cover the devices that we use for mixers, which are diodes and transistors. We will see, how those function as a mixing devices, and then we will also discuss the analysis of various mixer circuits that are used to implement mixers.

Thank you.