Integrated Circuits, MOSFETs, OP-Amps and their Applications
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Lecture – 31
Working of Crystal Oscillators

Hi welcome to this particular module and this is a lecture series that we are looking at oscillator's right. So, until now we have seen what exactly oscillator is, then we have seen how you can use operational amplifier as an oscillator, then we have seen kinds of oscillator and the criteria right. What is criteria? Phase shift should be 0 and that is phase shift is the output voltage that is feedback through the feedback network to the input of the oscillator should have 0 degree phase shift.

Second condition was the gain into feedback vector beta should be more of gain into beta should be greater than or equal to 1, initially we keep it greater than 1 to start the oscillations and then we make it equal to 1 to sustain the oscillations right. Then we have seen the use of R and C right. So, using resistors and capacitors end of the feedback network what we can get, we can get a, we can we can design a phase shift oscillator right. So, we have seen how the phase of oscillator can be designed.

Then we have seen that there are some cases where your amplifier that we use in the oscillator will not give you any phase shift, in that particular case you have to use a feedback network without any phase shift correct. Because amplifier and the output is not giving any phase shift; that means, output of the signal output signal or the signal at the output of the amplifier is in phase with respect to input. In that case the same phase will go to the input of the oscillator through feedback network.

So, feedback network should not have any kind of phase shift right, that is what we have seen there was a case of wein bridge oscillator and this rc oscillators are oscillators that are used at lower frequency. For higher frequency we have to use oscillators that are using L that is inductor and C is a capacitor right. So, these are the oscillator that are using L and C as reactances or reactive components these are reactive components.

Then we have seen how the L and C oscillators that is tan oscillators can be used for generating the signal oscillatory signal. So, for that we have seen that how the, initially we can take a condition where the capacitor is charged and then it discharges when an inductor is connected and then inductor is magnetically charged and then it discharges back the capacitor charge in the opposite polarity right. This opposite polarity comes because of the Lenz law that we have seen in the case of lc oscillators right.

Then once we understood how the L and C can be used as a feedback network we have designed 2 types of oscillator, the first one is a Hartley oscillator and the second one was colpitts oscillator. Now, if you remember our trick to understand how many capacitors and how many inductors you have to use, in which oscillator you have been seen that in a colpitts oscillator you can easily say that it is 2 capacitors, 1 inductor right, while in Hartley oscillator there were 2 inductors and 1 capacitor.

Then we have seen few examples; now let us see the case of another kind of oscillator which is called crystal oscillator. So, before we go to the crystal oscillator there is a property called piezoelectric property. So, you guys have to understand what exactly piezoelectric property means right and at the same time you also need to understand what is a piezo resistor property means because there is lot of confusion I have seen that, when I ask a student what do you mean by piezo resist to you the definition will be of piezoelectric.

And when we ask what is piezoelectric the definition will be of piezo resistor. So, do not get in confusion, piezoelectric crystals is the crystal that when we apply a pressure you will see the change in voltage, you will same change in voltage. Crystals shows some of the crystal source piezoelectric property, applying pressure can show change in voltage. Another one is piezo resistive applying force or pressure will show change in resistance, will show change in resistance resistive electric you see that is what is electric voltage is electric.

What is resistor? Resistors is a resistance. So, there is change in the resistance in the piezo is a resistive material there, just to have a basic definition of what is piezoelectric and what is piezo resistive sensors or piezo resistive and what is piezoelectric definition of what the terms.

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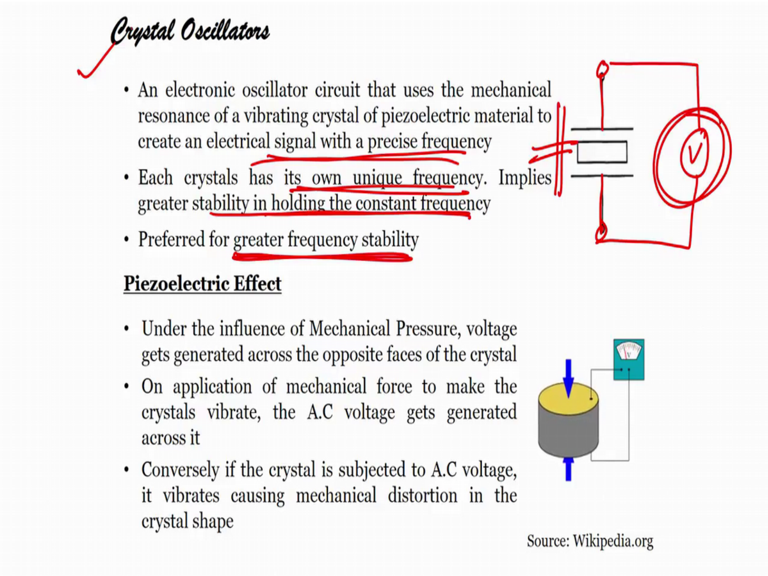

So, if I now talk about the crystal oscillators let us come let us see the screen and what we see here is that an electronic oscillator circuit that uses mechanical resonance of a vibrating crystal of a piezoelectric material to create electrical signal with a precise frequency.

That means that this is a crystal that is used right, we draw a crystal like this right this is this entire lisa crystal actually. So, we this a crystal and then we had taking the output of the crystal right and this output will be nothing, but electrical signal we can say voltage, we can say voltage this voltage is generated, this voltage is generated because of the mechanical resonance of this particular crystal.

How this will mechanically resonate when we apply pressure, when we apply some pressure it will start resonating this resonance will caught the vibrating crystal piezoelectric material, this material is piezoelectric and there will be change in the electrical signal. Each crystal has his own frequency and implies greater stability in holding the constant frequency.

So, every crystal has his own frequency and it can hold or it can have a stable frequency response prefer for greater frequency stability. So, when you have, when you want to have a stable when you want to design a stable oscillator the crystal oscillators are preferred are preferred over other kind of oscillators. Now, what do we see piezoelectric effect, just now we have discussed let us see once again. Under the influence of mechanical pressure, under the influence of a mechanical pressure voltage get generated across the opposite faces of the crystal.

You see here it is shown these are taken from the Wikipedia, you can see here we are applying the pressure the crystal is deforming you see, you see this one see it is moving. When it is when we apply a mechanical pressure there is a change in voltage, you look at this meter right applying pressure voltage increases, releasing pressure voltage comes back. So, applying pressure will change will cause change in the change in the voltage or change in the signal ok.

Applying pressure wear across the faces of the crystal, on application of mechanical force to me crystal vibrate the A.C voltage gets generated conversely if the crystal is subjected to A.C voltage it vibrates causing mechanical distortion that is that in a, if I apply mechanical force, if I apply a mechanical pressure you can see the change in voltage.

But if I apply voltage, if I apply a voltage then you can also see change in mechanical distortion alright cool. So, vice versa is also a possibility all right cool. So, this is what your, this is what your piezoelectric effect means.

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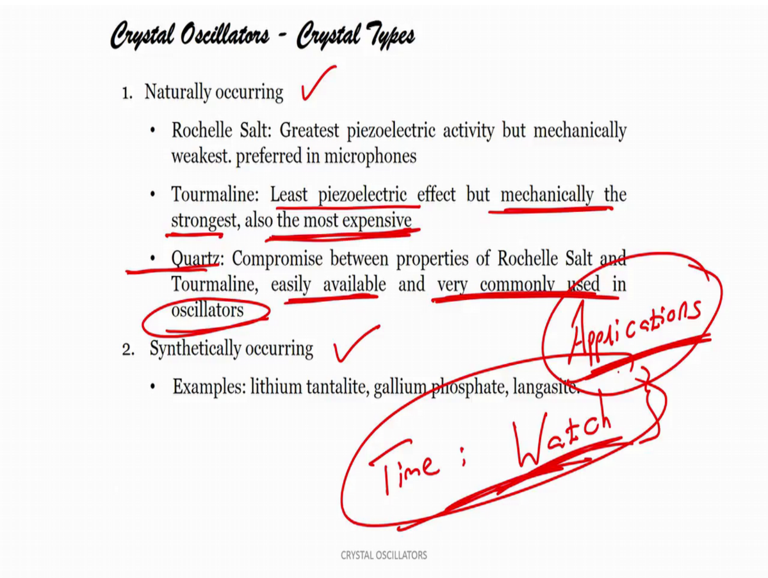

Now, when I talk about crystal oscillators, what are the crystal types we have to understand right, then only we can see which type we can use it. So, when we talk about crystal types what a one first is naturally occurring crystal types right, naturally occurring and second one is synthetically occurring crystals one is naturally occurring second is synthetically occurring.

So, Rochelle salt has the greatest piezoelectric activity, but mechanically weakest. So, this is the greatest piezoelectric activity; that means, that a small change in mechanical pressure can cause a huge change in output voltage, but mechanically weakest. So, mechanical they are very weak and not strong enough to withstand higher mechanical pressure that is why they are mostly used in microphones, you see. So, now, we can say that if I want to have if I want to generate a voltage when I apply pressure and it should be sensitive then we can use a Rochelle salt alright.

Let us see another crystal called thermal line and this crystal is at least piezoelectric effect, but mechanically it is robust or strongest and it is also most expensive you see least piezoelectric effect, but mechanically strong. Let us see the third one, quartz we have seen right many times, quartz compromise between Rochelle salt and tourmaline easily available and very commonly used in oscillators, very commonly used in oscillators alright.

So, think about where this quartz crystal oscillators are used, what are the applications what are the applications of quartz crystal oscillator and what does a watch do, what is our watch hand watch which was time right time. Is there crystal is there an oscillator in a watch, look at it applications of course, crystal oscillator see what is there within a watch within a watch, look at it cool.

So, now these are naturally occurring, let us see synthetically occurring, let us see synthetically occurring. So, examples are lithium, tantalite, lithium tantalite gallium phosphate, langasite. So, these are all synthetically occurring crystals.

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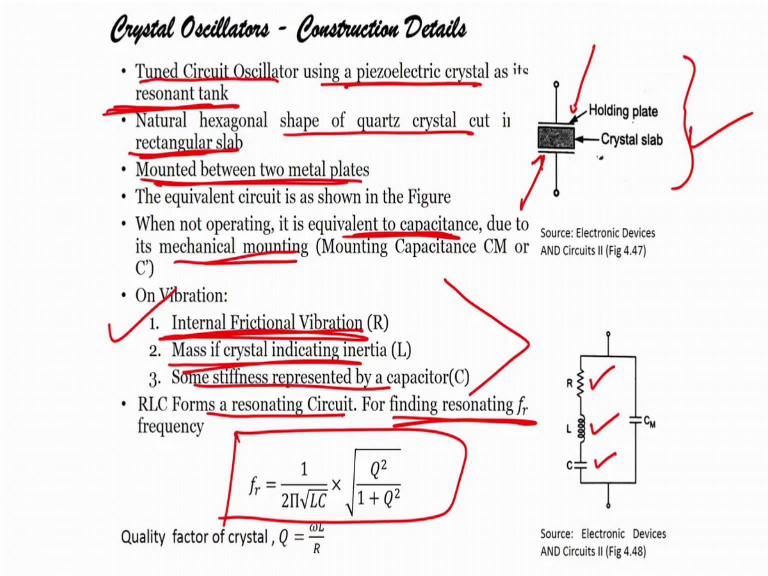

Now, let us see how we can design the crystal oscillator, how we can design the crystal oscillator or you can construct crystal oscillator.

So, what we see here is a tuned circuit oscillator using piezoelectric crystals as its resonant tank. So, what is that, you see here tuned circuit oscillator using a piezoelectric crystal as its resonant tank natural hexagonal shape of quartz cut in the octagonal shape. So, we are using a hexagonal shape of quartz crystal cut into rectangular slab to construct the crystal oscillator.

Now, this clear crystal is placed or mounted between 2 metal plates which you can see here right. We are not operating its equivalent capacity is equivalent to a capacitor due to its mechanical mounting right because you have a conducting plate, you have a conducting plate when it is not operating is like a 2 conducting plates separated by some material by some dielectric material.

Now, on vibration interval frequency vibration mass if the crystal in is, if mass if crystal indicating inertia and some stiffness represented by capacitance c. So, on vibration we have these 3 components R, L and C that you can see right over here, the on vibration this is it this is just a capacitor when it is not operating, but when is operating then there will be a resistance, resistance is because of the internal frictional vibration one ok.

Then because of the mass if the crystal indicating inertia. So, there will be L and some stiffness represented by capacitor C, thus this RLC comes into picture. Now, RLC forms a resonating circuit for finding as analyzing frequency fr we have to use f r equals to 1 by 2 pi under root of LC into under root of q square divided by 1 plus q square where quality factor is, quality factor of the crystal is given by q equals to omega L by R..

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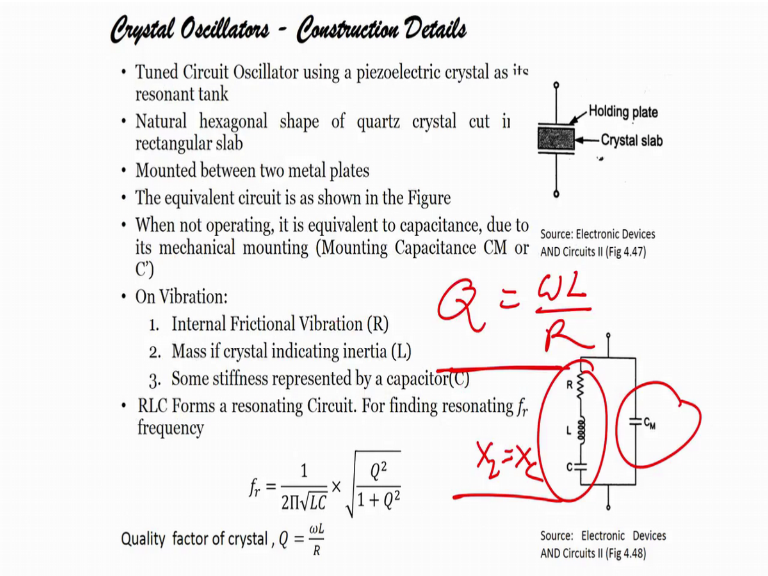

Quality factor q is given by omega L by R this is the quality factor of the crystal alright.

So, what we understood that when the crystal, when the crystal oscillator or a tuned circuit is not functional it acts as a capacitance, when it is functional when it is vibrating it will have RL and C in its equivalent.

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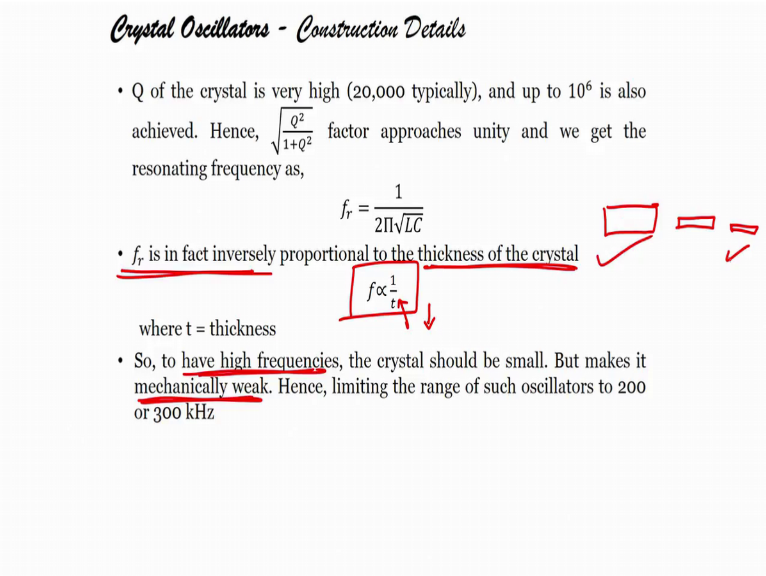

So, q of the crystal is very high you see and up to 10 raise to power 6 or 10 to the power 6 is also achieved hence under root of q square by 1 plus q factor approaches unity and we get the resonating frequency f equals to 1 by 2 pi under root of LC correct.

Because if this which is unity then only we can have we can have q of 10 to the power 6. So, our formula will become nothing, but f r equal to 1 divided by 2 pi under root of LC then another factor that we have to understand or another effect we had understood that fr is in fact, inversely resonating frequency of a crystal is inversely proportional to the thickness of the crystal that is why we write f is proportional or inversely proportional to the thickness t.

So, to have high frequencies what we understood that it is inversely proportional. So, for higher frequency thickness should be small correct, thickness should be small, but makes it mechanically weak right. As you decrease the thickness of the crystal right, from here, to here, to here right which is mechanically weak this one is mechanically weak which is mechanically strong this is mechanically strong, but what can be used at a higher frequency, this can be used at higher frequency because thickness is low right.

But mechanically it is weaker, mechanical it is weaker that is what he is saying hence the limiting range of such oscillators would be 200 hertz to 300 kilo hertz or 200 hertz or 300 kilo hertz. So, this is how the crystal frequency crystal oscillator frequency is determined and it has to depend on thickness just to understand that we cannot make it too thin, otherwise it will be mechanically weak we have to limit our range of oscillations to around 200 or 300 kilo hertz very easy so for as you see right now.

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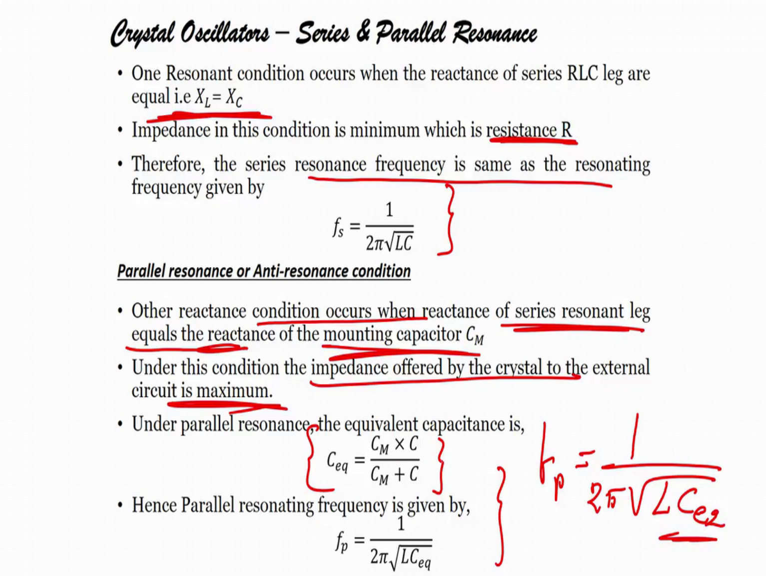

Let us see another thing. So, once the resonant condition occurs when the resonance, reactance of series RLC leg are equal to xl equals 2 xc alright. So, when this condition occurs then the resonant will start occurring impedance in this condition is minimum which is resistance R therefore, the resistance series resonant frequency is same as the resonant frequency which is given earlier right. So, what it says that, when the once the resonance condition occurs right the xl will be equal to xc in that case the impedance R would be minimum obviously.

So, therefore, the series resonant frequency is nothing, but equal to d, equal to the resonant frequency right the resonant frequency is same as the resonant aj this original frequency is equal to the resonant frequency of the oscillator that is why the formula for series resonant frequency is same is same like we have seen earlier. Now, what if a parallel resonance or anti resonance condition occurs. So, what does that mean that other reactance condition which occurs when reactance of series resonant lag equals the reactance of the mounting capacitor C m right.

There is a mounting capacitor if you see here there is a mounting capacitor C m right and this is when a resonant starts then there xl will be equal to xc, but what if, but what if the reactance condition occurs when the reactance of series resonance leg equals the reactance of the mounting capacitor. That means, that this reactance, the series the reactance occurs occurring due to this series the components that are used in series, it is equal to the mounting capacitor C the reactants are mounting capacitor is equal to reactance formed or obtained by this series resonant series resonant leg ok.

So, in that case under this condition the impedance offered by the crystal to the external circuit is maximum right, under parallel resonance circuit parallel resonance the equivalent capacitance we can give C M into C by C M plus cy because the impedance offered by the crystal direction circuit will be maximum when you are when you are series resonant leg equals the reactance of the mounting capacitor C M.

Hence the parallel resonant frequency is given by f p equal to 1 on 2 pi under root of LC equivalent force equivalent is nothing, but your C M into C by C M plus C you see. So, let us see now.

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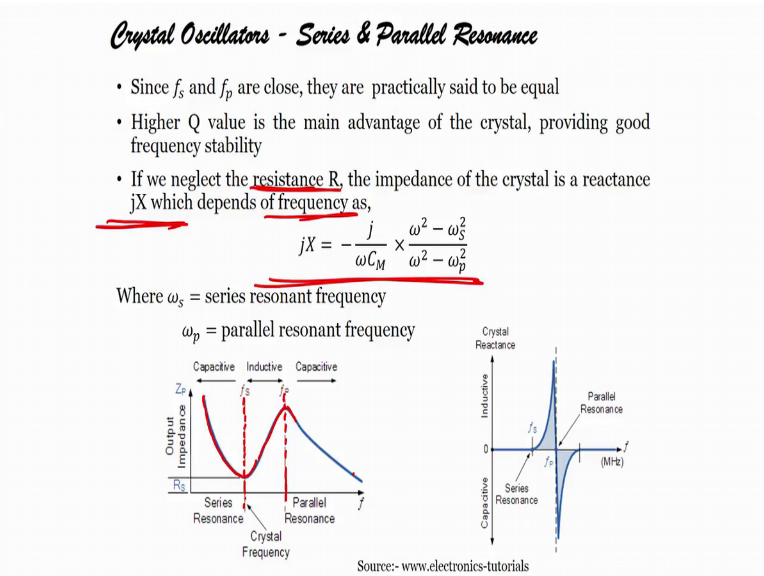

Since fs and fp are close right, they are practically said to be equal higher q value is the main advantage of the crystal providing good frequency stability right, it has higher q; that means, this frequency is extremely stable.

So, if we neglect resistance R the impedance of the crystal is reactance jx which depends on frequency with the formula shown here right. If we are neglecting resistance R or your impedance unity will be nothing, but the reactance j o x which is nothing, but minus j by omega C M into omega square minus omega square divided by m omega square minus omega p square where omega is nothing much series resonant frequency and omega p will be nothing, but parallel resonance frequency right.

So, in series resonance frequency you can see output impedance here and you can see parallel resonance frequency. So, here when you see this is a crystal frequency, when it is in series like fs and also this is resonance will cause the impedance to decrease at what we have seen and then when it is in parallel resonance which is f v again it will reach to a peak and then finally, again this will be forming.

So, this is how the these are the oscillations will occur, these are just a representation of how series resonance and parallelism and circuit during series resonance how the signal would be how the output impedance would be compared to when these parallel resonance alright.

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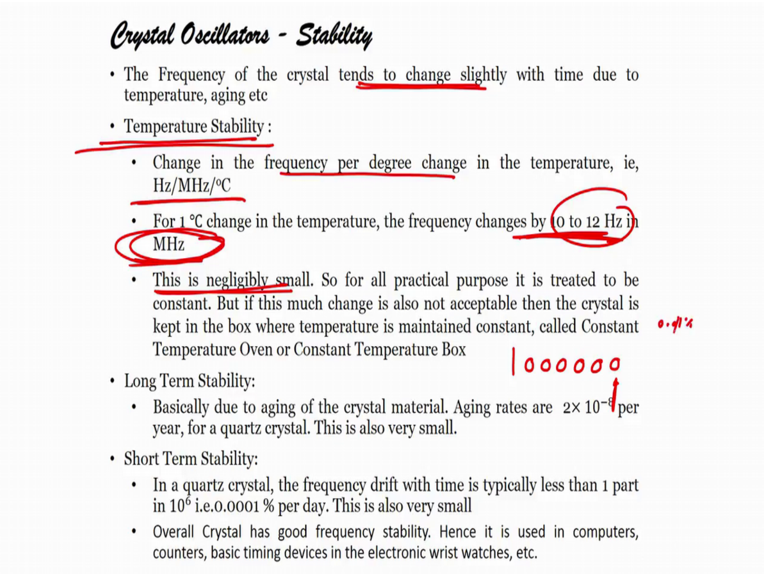

So, if you talk about stability further, the frequency of the crystal tends to change stability change slightly with time due to temperature aging etcetera.

So, now another point is that when we are using crystal it has a, it has a lifetime. So, as the time increases or when did when the temperature is changed or when it is aging by this time, then the frequency of the crystals, tend to change slightly. So, temperature stability, temperature stability change in the frequency per degree change in the temperature that is hertz or mega hertz per degree centigrade, for 1 degree centigrade change in temperature the frequency changes by 10 to 12 hertz alright in megahertz for 1 degree we have to we will see that or we had to understand that the change is by 10 to 12 hertz. This is negligibly small why because we are talking about megahertz, in megahertz if I have 10 to 12 hertz change it is very less because mega is mega hertz is 1, 2, 3, 4, 5, 6 right, 1 mega hertz.

Now, what I am talking about frequency changes only in this value right. So, if I have this, this will be very less about 0.201 percent or 0.1 percent right. So, very less very less. So, that is why if there is a 10 to 12 hertz in 1 min in megahertz range that is, I am just talking about one mega it can be several mega hertz right then in that case the change in temperature, the change in temperature is not going to change the frequency that is significantly, that is why we can say that the change in the frequency on the change in temperature is negligibly small.

So, for all practical purposes it is stated to be constant right, since it is negligibly small for practical applications we assume that the frequency is constant even there is a slight change in temperature, but if this match this much change is also not acceptable then the crystal is kept in a box where temperature is maintained constant called constant temperature oven or constant temperature box alright.

So, in some of the cases even the smallest change in the temperature will cause a little bit change in the frequency which is 10 to 12 hertz for 1 degree right. So, for 2 degree it will be 24 hertz if 3 degree there will be more. So, 36 hours and so on and so forth, but if that much also change in frequency is not acceptable in some of the circuit where we require the crystal to give us exact frequency, stable frequency and there should be no effect of temperature then we had to keep the crystal in a box called the called the constant temperature box or constant temperature oven alright.

To get a more stable frequency why, because now we are talking about the removing the effect of temperature we do not have the temperature effect on the crystal because it is kept within a constant temperature box right. So, that is about the temperature stability, how about long term stability.

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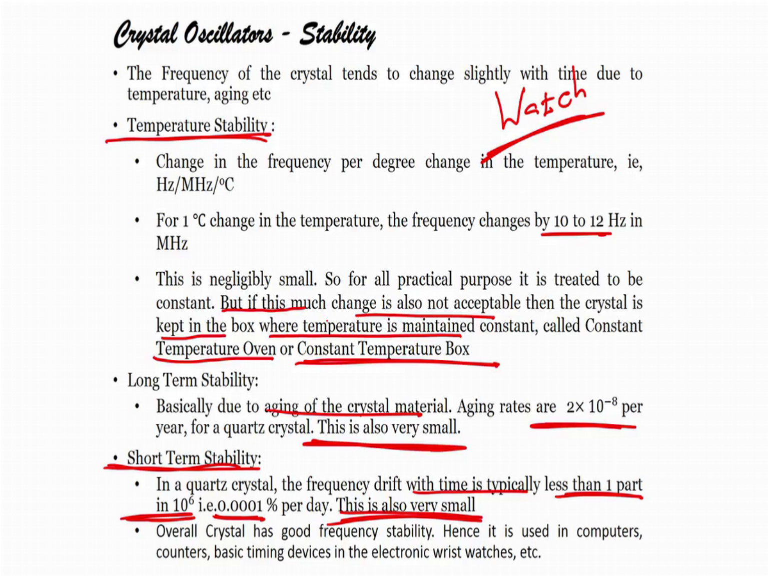

When I talk about long term stability then what we see basically due to aging of crystal material right the aging rates are 2 into 10 to the power minus 8 per year, per year for crystal this is also extremely small right. 2 to the power minus a, 2 into 10 to power minus 8 per year this is super small right very small.

So, basically due to aging the crystal material the aging that is so small. So, that is why it is long term stability is also kind of excellent, short term stability in a quartz crystal the frequency drift with time is typically less than 1 part in 10 to the power 6, 1 part in 10 to the power 6 is 0.0001 percent per day this is also extremely small this, is also extremely small.

Now, I asked you a question what a watch consists of right, the previous slides and I have given you answer also in this slide. So, you see you see here where is the answer, answer is here can you see that over all crystal has a good frequency stability hence it is used in computers, counters, basic timing device, in electronic wrist watches in electronics wrist watches ok.

So, now you know that frequency stability is very important when we talk about the oscillators and that particularly crystals when crystals are. So, stable that they are used in many applications including computers, including counters, including basic timing devices, including your digital wristwatch all right. So, there are this application of the crystal. So, now, since we kind of understand that what are the equation for f s we know, what is the equation for C equivalent we know, what is the question for f p we know.

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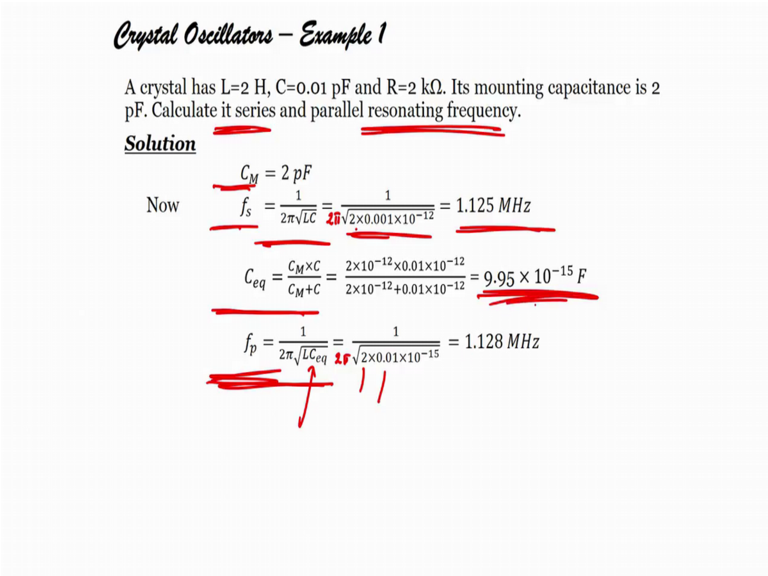

So, if we know everything let us try to solve a problem all right, let us say to solve a problem.

A problem is a crystal has inductor L equal to 2 Henry C equals to 0.01 picofarad R equals to 2 kilo ohm it is mounting capacitance is 2 pico farad then calculated series and parallel resonant frequencies. So, is equation and the a solution is also very easy, we are given C m now we have to see f s f s is series resonant frequency series resonant frequency f is nothing, but 1 by 2 pi under root of L C.

So, one by under root of this one when you solve it what you will get 1.125 megahertz alright you will find the value 1. So, how if you see L is what 2 henry right, then C is 0.01 capacitor and we have to write 2 pi, 1 by 2 pi under root of 2 number of 2 into 0.001 into 10 to power minus 12 that will give us the fs, of 1.125 mega hertz excellent.

Now, we know what is fp, fp is 1 by 2 pi under root of LC equivalent; that means, we have to find C equivalent and now for finding C equivalent we should know the formula, we already know the formula C equivalent is nothing, but cm into C divided by cm plus C if that is the case we will put the value of C M C M is 2 picofarad and ce is 0.01 pico farad. So, 2 into 10 to power minus 12 into 0.01, 10 to the power minus divided by 2 into to a power minus 12 plus 0.01 to 10 to power minus 12 that will give us nothing, but 9.95 into 10 to power minus 15 farads.

So, now we know what is equivalent, substituting value of C equivalent in the equation of f p we get 2 pi under root of 2 there is L is 2 henry into 0.01 this 1 right 10 to the power minus 15. So, or when we solve this we will get, will get the answer close to 1.128 mega hertz, will get answer close to 1.128 omega it is easy, let us see another example.

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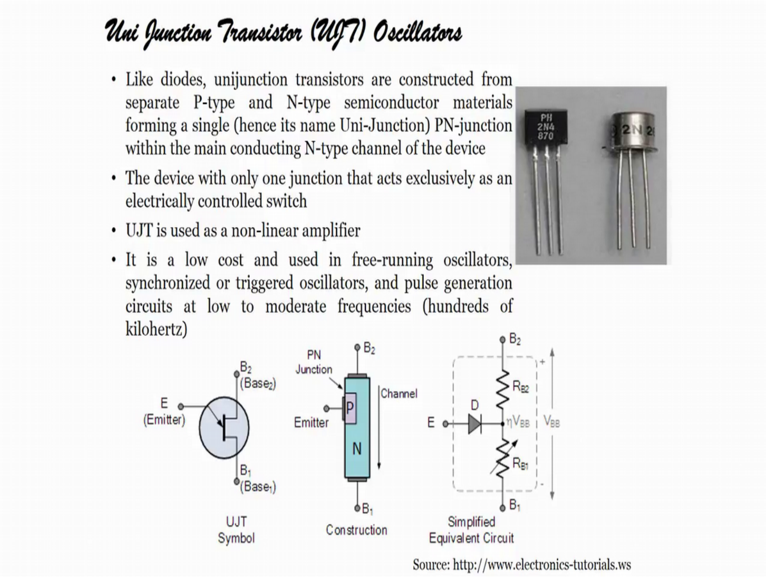

So, now this is the example of the uni junction, uni junction transistor or ugt or status before move before we move to UJT oscillators let us understand quickly about crystal oscillators quickly and then we will take the UJT oscillators in the next module, we will see the UJT oscillators in the next module.

So, what we have seen until now is how the crystals can be used in oscillator and then what kind of crystals are available which shows the piezoelectric properties, isn't it shows the piezoelectric property and then we have seen that which crystal is more stable, which crystal is more stable and then we have seen how we can use this crystal as an oscillator and what are the kind of frequency formula that we can find whether this fs whether this fp and then we have to try to solve a solve few problem.

We also saw that these crystals are extremely stable and hence they are used in many applications which were discussed in this particular module. So, now, you know what are phase shift oscillators, you know what is Wein bridge oscillator, you know what is colpitts oscillator, you know what is Hartley oscillator you also know what are the crystal oscillators right. Now, in the next module let us see what are UJT oscillator or uni junction oscillators.

So, we will we will stop in this lecture in this particular on this particular crystal oscillators and let us see in the next module what are the other kind of oscillators alright. Till then you just look at these slides look at what I have taught, understand thoroughly what does what how exactly the oscillator works if you have missed the earlier modules go back and see earlier modules and see how what are the barkhausen criteria and how the oscillators were designed. So, I will see in the next class till then you take care bye.