Compliant Mechanisms: Principles and Design
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Lecture – 63
Micromechanical signal processors using compliant mechanisms

Hello, we are into micro systems and the role compliant mechanisms play in micro systems applications. So, we are going to discuss something very unique which is mechanical signal processors that use naturally compliant mechanisms because we want to have elastic elements arranged in various ways, so as to perform the function of signal processing. Let us look at what we mean by Micromechanical Signal Processors.

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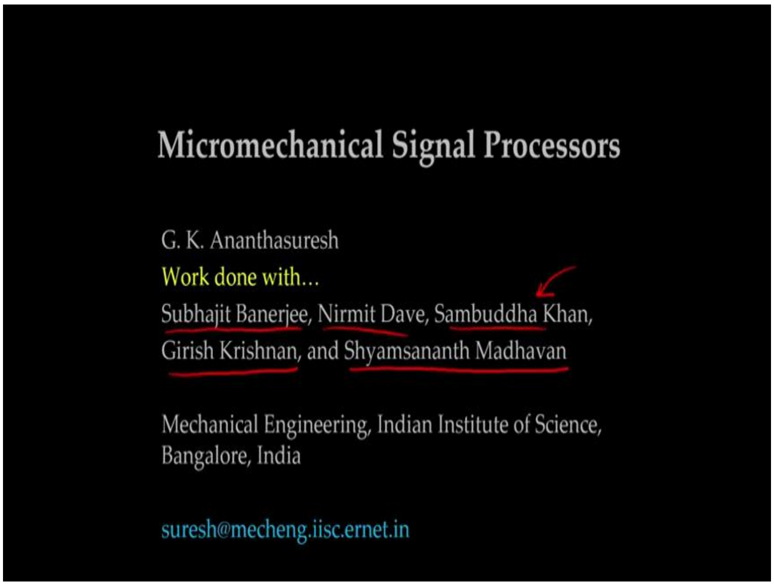

This was a work done with a number of students as is anything that I am talking about, in this particular case, Subhajit Banerjee and Nirmit Dave, Sambuddha Khan, we are going to talk about his work on micromachined accelerometer later on and Girish Krishnan who started it at IISC in various ways is that you are using now and Shyamsananth Madhavan who worked on force amplification mechanisms among other things.

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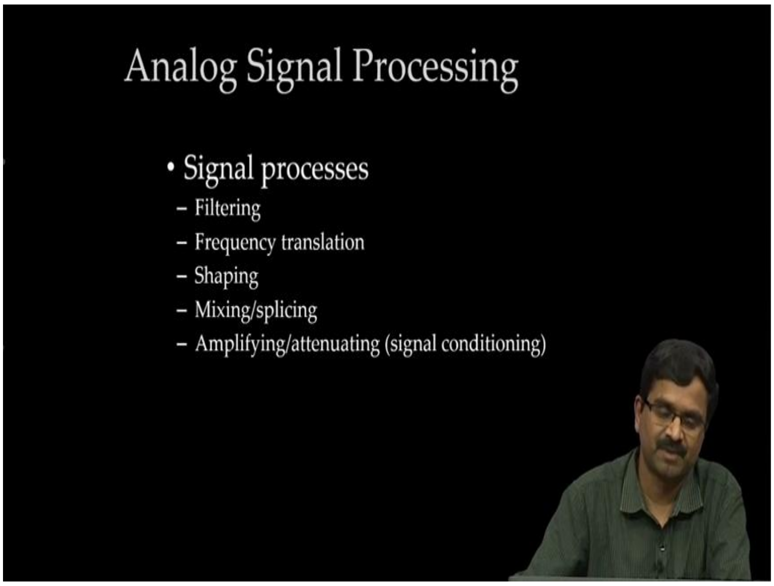

First question is what is signal processing? So, signal processing if you think about analog signal processing we have filtering, frequency translation that is one frequency signal of one frequency now changed to signal of another frequency we can do signal shaping let us I give sorted to 1 and you convert that to sinusoidal or the a step 1 converted to sort 2 then such things. And we can do mixing and splicing of signals, we can also amplify and attenuate and we can do signal conditioning and number of others.

We will just take a few of this and understand how we can do that with compliant suspensions and compliant mechanisms.

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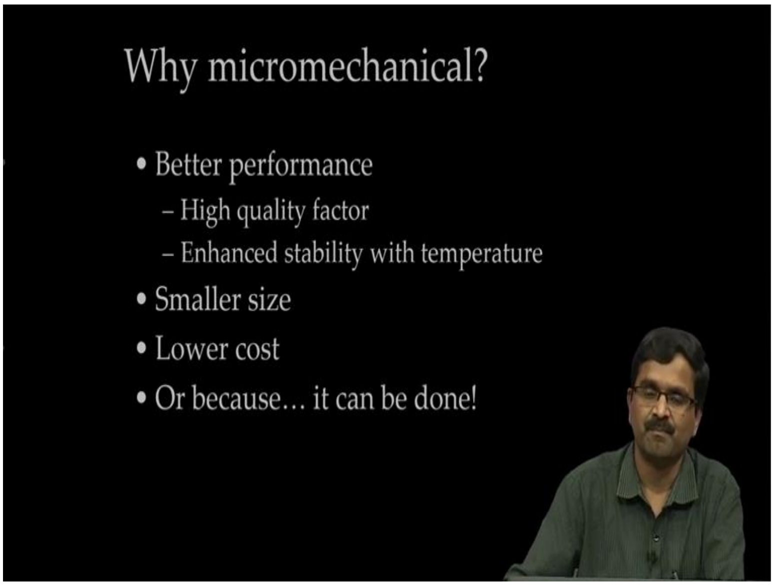

First question is why micromechanical signal processing? Why micromechanical? There are number of reasons that people have worked on it and identified that we get actually improved performance with micromechanical signal processors than micro electronic signal processors. So, at microelectronic things are widely used, but now in the last couple of decades people have realized that using micromechanical signal processors is actually beneficial and you have better quality factor and better stability with temperature and of course, the size is much smaller than what microelectronic process would use that may surprise you, but it is true.

As I have show one example, where the size of a mechanical signal processor is smaller than the equivalent function, micro electronic signal processors and lower cast when the size of a device becomes small in micro system business, the cost also becomes a smaller because on a same vapour we can make a lot more devices. Why micromechanical? Because it can be done, I guess people just want to do things to the extent of making clocks now micro mechanical clocks, we will talk to what are locks in one of the few previous lectures, but also clocks done in a way that we do not need a quartz clock in the future had some people are making efforts to make micromechanical clocks.

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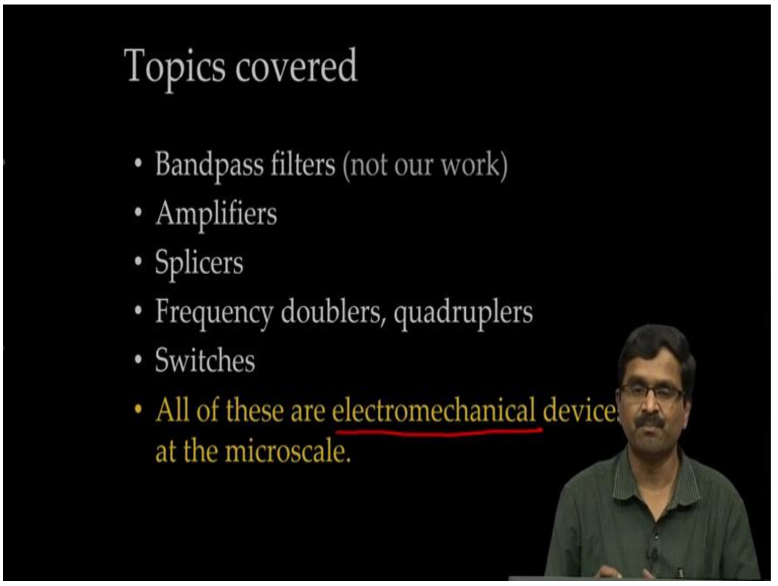

Let us look at some of these in this lecture: Bandpass filters - that is not our work that we will show any way and amplifiers, signal Slicers, frequency doublers and quadruplers and switches all of these are not purely mechanical devices. In fact, they are electromechanical devices happened to be at the micro scale. The electromechanical because they take electrical input as actuation and move or the movement causes some change in capacitance where we have to static devices or change resistance there, these resistive and so forth. So that basically intrinsic electromechanical devices, but the mechanical behavior is important for their function.

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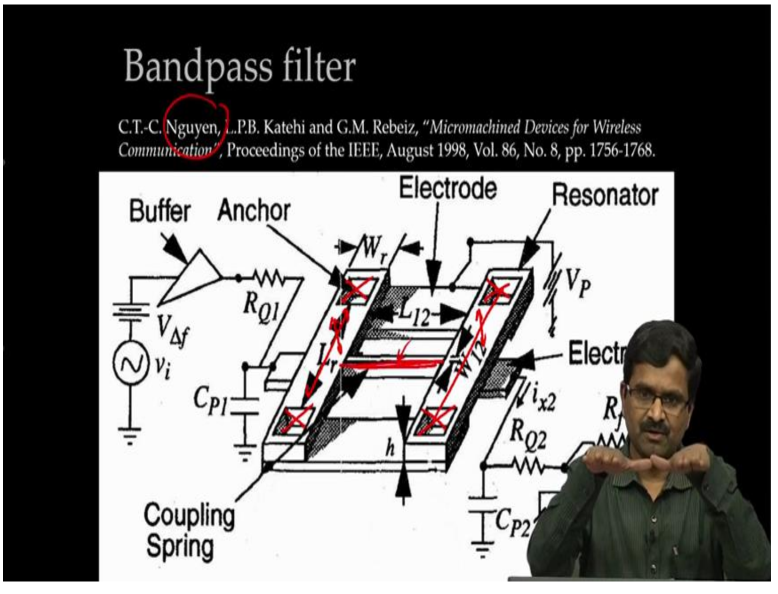

Let us look at a Bandpass filter micromechanical Bandpass filter. So, this is a work of Clock Nguyen, he has worked extensively on this and this is one of the early designs that he had come up with what you have is a beam which is fixed here and fixed here and another beam that is fixed here in between there is a third beam. So, there is a beam that can move up and down like this, up and down like this and these 2 beams are coupled by this thin coupling beam and that is enough for Bandpass filters.

You give this signal to let say this one and this is moving up and down and in a narrow band this coupling beam will transmit the motion to the other one you can pick up the output here. So, basically you have 2 beams which are coupled to each other now when one beam is moving up and down like this let us say this is moving up and down then this will also be moving a little, but at one frequency range you know the word called Bandpass range, this will also move a lot and that is why signal gets transmitted.

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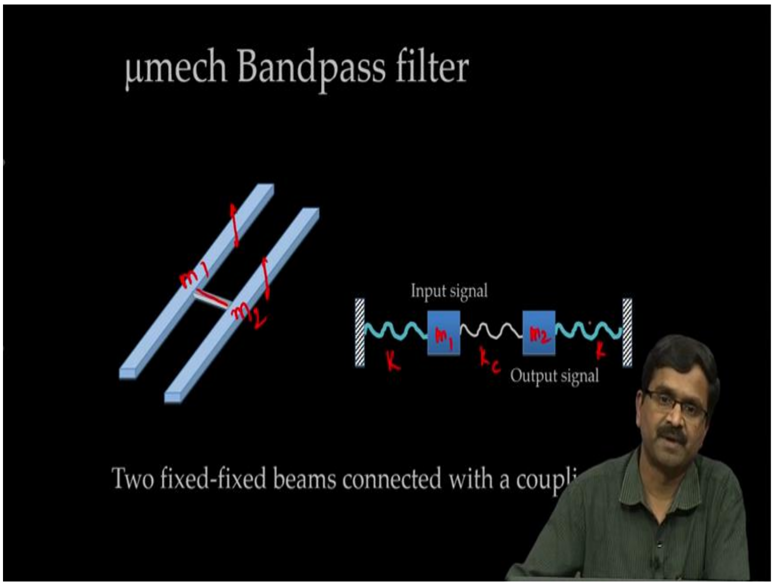

In order to look at that as a model let see that this is 1 beam that moves up and down another beam that moves up and down and this is the coupling beam how do you represent it? It is like this; the mass of this, so there is this mass m 2 and m 1. So, we have m 1 and m 2 of course, these things are now shown to move in plane, but it could also be out of plane.

There are spring, this is the coupling beam spring and this is the suspension beam thin, if you give the input signal here it definitely goes output, but for a frequency range there will be a lot more displacement here and that is where you get the Bandpass filter function.

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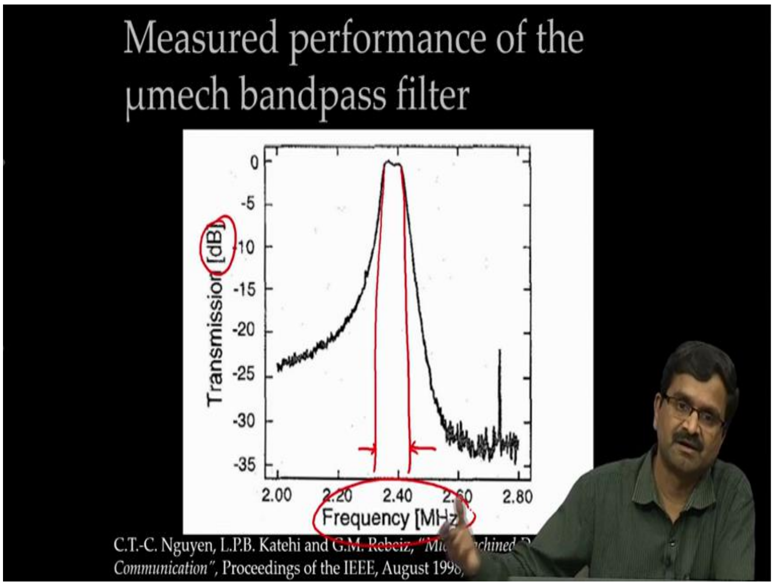

If you look at the transmission versus frequency how much of forces or a signal or motion in this case is transmitted over this band you can see these all decibel scale d b a lot more than the other places. So, it acts like a Bandpass filter.

In that frequency you will transmit the motion other things it does not that is what a Bandpass filter, does what you need here simply couple of beams nothing else, 2 beams in the coupling beam you can make it as small as the gate in the transistor. So, electronic Bandpass filter just cannot complete because if I want to make a filter you need a few electronic elements, may be at least if couple of transistors that or resistors and capacitors here all we need is couple of beams with a coupling beam that is all. So, you can make it very compact and the performance actually is much better because the quality factor is quite high for these things for micro electro mechanical devices and the frequency also this mega hertz, but there are gigahertz instance of gigahertz also made using micromechanical beams these also like a suspension in a way couple of beams are suspended and that search the function of a Bandpass filter.

Let us look at micromechanical amplifiers, we are going to see a lot more of it in a lecture in a future lecture on micromachined accelerometers and let us look at what a compliant amplifying mechanism can do for MEMs.

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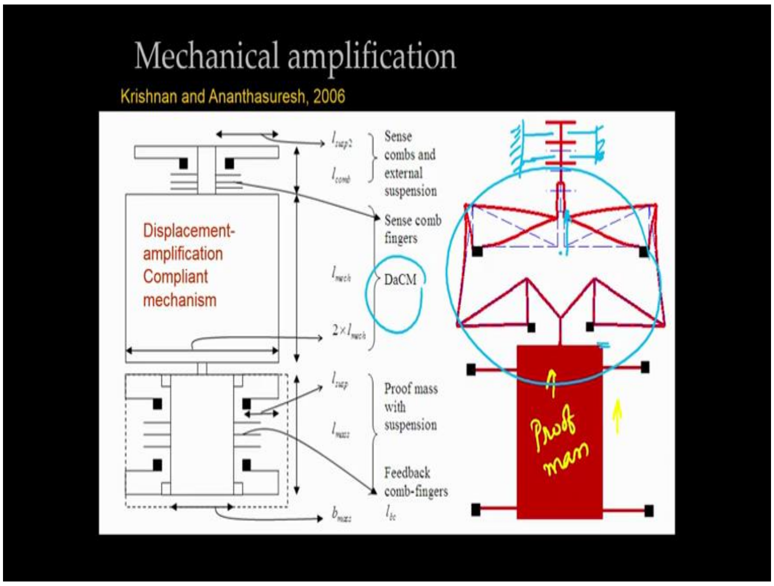

Here is a an accelerometer where we have the proof mass, this is the proof mass then there is acceleration which going to move, if I measure the displacement of this mass here that is not going to be very much instead if we measure someplace else if we measure someplace else meaning over here see how much it as moved so much and you can hardly see any displacement of this.

When you want to have an accelerometer that gives you a lot more displacement so that If you put electrostatic comb device here. So, this is a moving comb and if you put a fixed comb here the capacitance change in this will be so much more and you get you few more accelerometer to become very sensitive. So, in this particular case a displacement amplifying compliant mechanism gives you enormous sensitivity enhancement.

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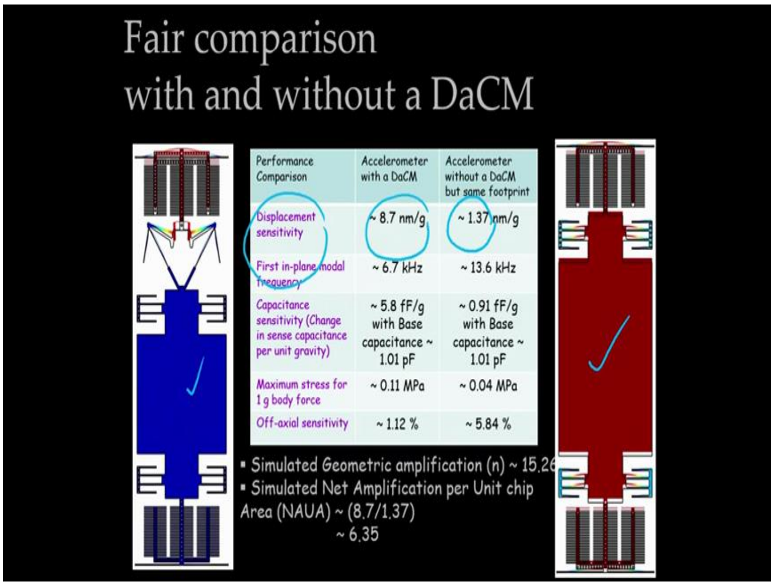

And occupying the same areas as you will see in another lecture if we look the thing that is here with a DaCM and one without DaCM they both occupy the same space whereas, the one with DaCM is going to give you a lot more, this particular case this gives you 8.7 nanometer per g action to gravity sensitivity whereas this is only 1.37.

There is almost more than 6 times or in 7 times amplification in sensitivity that happens, but both occupy the same space, we will talk more about it later on.

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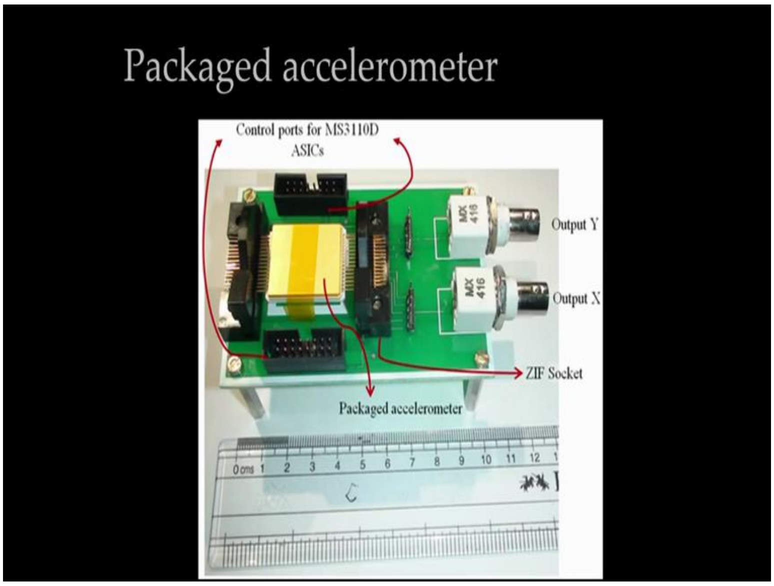

Completely packaged and tested and you know done everything again the details will come in another lecture.

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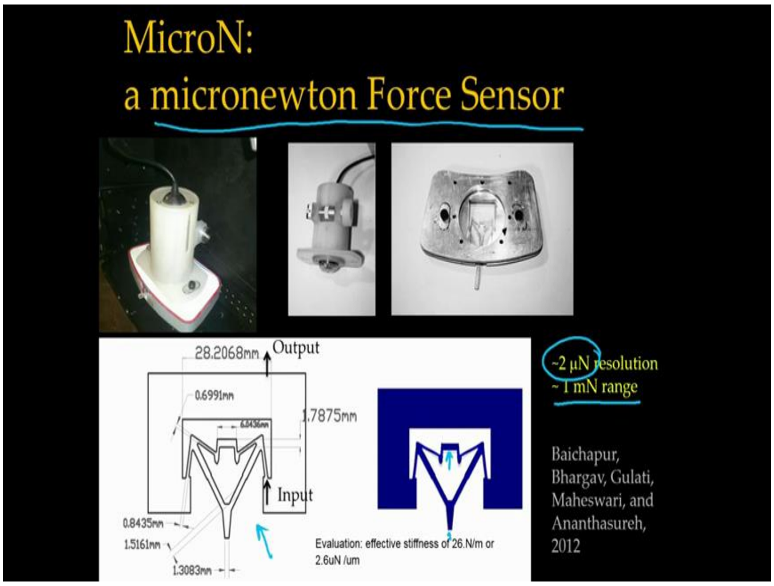

Now let us look at a micronewton force sensor that also uses a compliant mechanism that is shown over here, we may apply some force this is going to move a lot more and give you in 1 millinewton range the resolution about 2 micronewtons.

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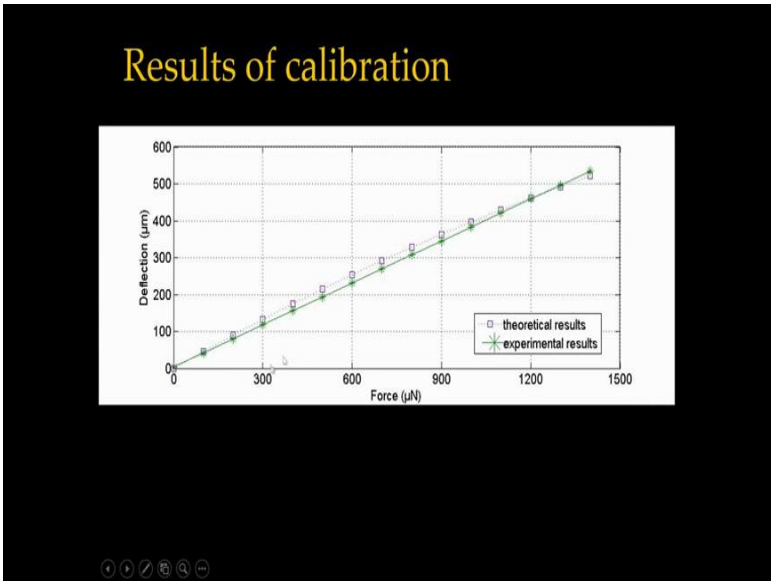

We are going to have another lecture on this one; right now what we do is the movie place we will see otherwise we will see in another lecture. I think movie file is not here and it gives you fairly linear characteristic with the experimental theoretical things compared giving you 2 micronewton resolutions for the force.

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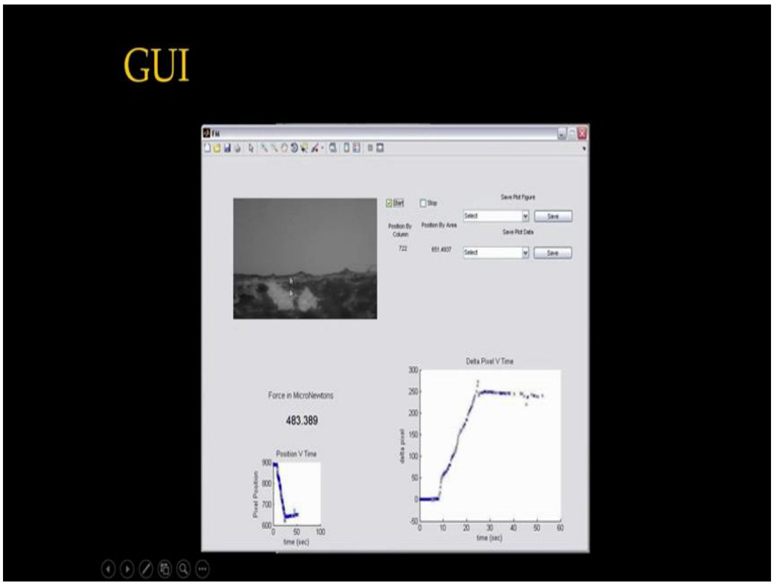

And this is the interface for it, we look at it in another lecture.

Now we can also do for force amplification, just like this displacement into force and that is also used in another type of accelerometer which is called Resonant Accelerometer.

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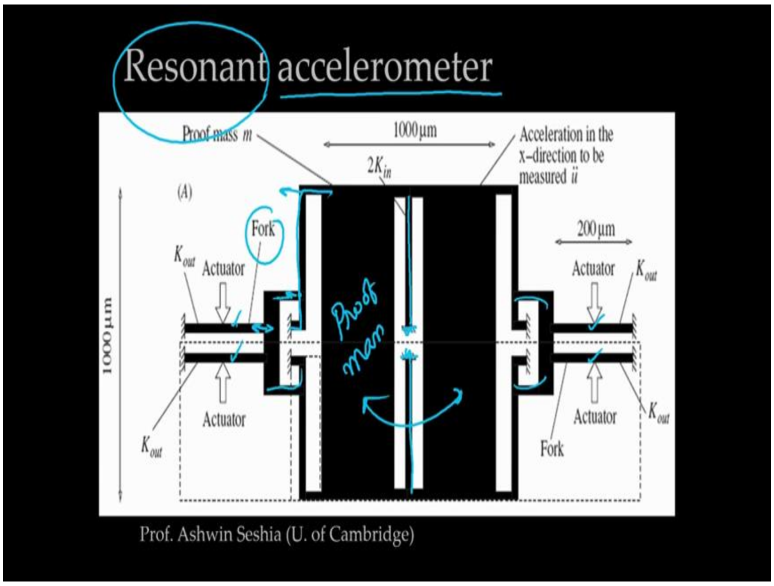

What you do here is over here, we always we have a tuning fork type of device, we set it into motion, we see what its frequency is. Now if there is acceleration, this is the proof mass and there is a proof mass on both sides and that is your interesting way to suspend it here this is a suspension actually. So, this is suspended mechanism on both sides for the proof mass and there is also a lever right. So, it is like a pivot then there is proof mass move like this, this moves much less and hence there will be force amplification. So, this one will either compressed or extend this tuning fork beams.

Whenever there is acceleration when this proof mass applies force in amplified because of this leverage this will be amplified force over here and here and here and here and this beams this beams, I will click on them, 1, 2, 3, 4, beams they will be pulled or pushed. When that is done their natural frequency changes which you will detect by looking at a resonant that is you resonate them at various frequencies and find what the natural frequency is and that will tell you what the acceleration is.

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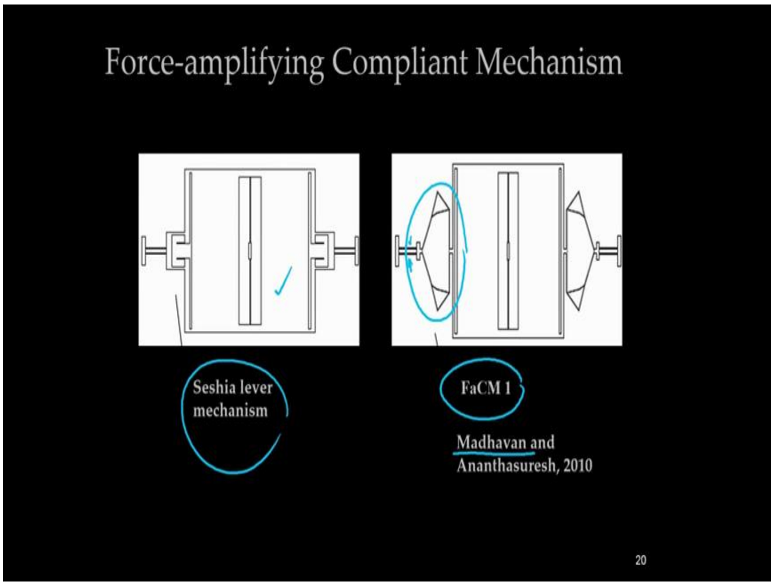

Again coming with suspensions is important here as was done this was one mechanical literature what Shyamsananth Madhavan had done using FaCMs that is force amplifying compliant mechanisms. We have a few mechanisms of that kind also these are force amplifying mechanisms there were design using optimization where you can have the natural frequency in the beams that are here and lot more change for the same acceleration compare to the one that we just discussed. So, again compliant mechanism plays a role here.

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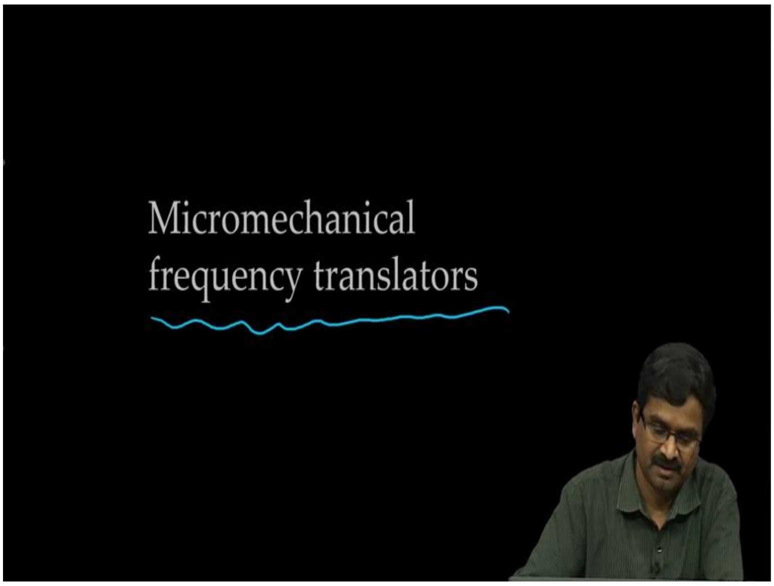

These are all signal processing. So, far we talked about Bandpass filters and display amplification that is like a motion signal conditioning amplification or force now let us actually the frequency translators meaning that if you send a signal of certain frequency mechanically it will be convert into another signal that has a different frequency, how do we do that mechanically?

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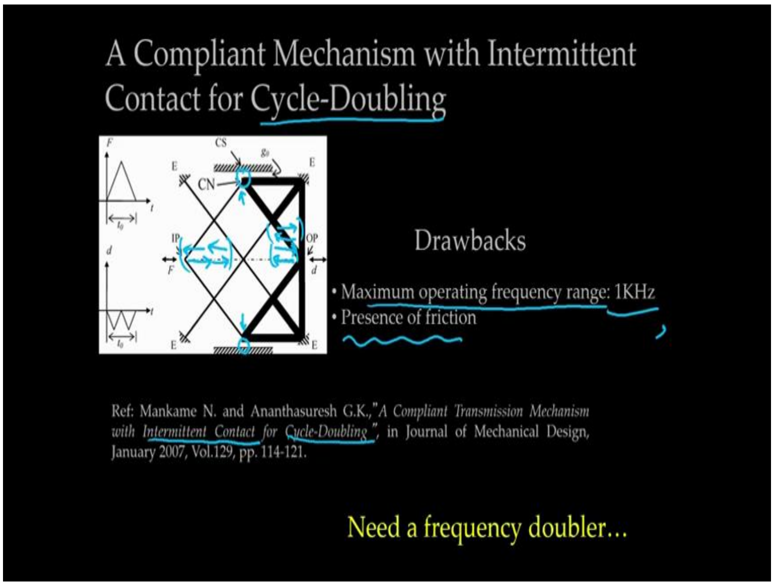

Here first let us talk about cycle doubling feature. So, here is a compliant mechanism which has input here when we will apply force over here what will happen to the output is that the way this is designed output will start moving in that direction as output moves here these points are going to move like that and after a while the contact takes place here. Once a contact takes place this output which has moved from here to here, will go back here, this input moves a little bit more output will go back to the same point. Now when you reverse this, this will first reverse like this and then you go further here then this will go back here.

What you see is that one cycle at the input creates 2 cycles at the output, this is a cycle doubler. So, if you have input coming like this output let say initially it comes back when you move further this actually goes back and when you go like this, this will come and when you go further original state will come back here. They both are back to where they are, but output has done 2 cycles input has done one cycle, this is a contact aided compliant mechanisms with intermittent contact not long duration contact and you can get the cycle doubling.

It is called cycle doubling because if you do too fast it may not work as well. So the drawback of this particular one was we are doing intermittent contact there is some fiction which you want to avoid in microelectronic mechanical systems, components and devices. And other thing is that there is a maximum operating frequency range beyond that this is of 1 kilo hertz which is too low for the compliant mechanisms. So, there is alternative that was done by a student named Nirmit Dave, it is a frequency doubler, what is cycle doubler becomes a frequency doubler as we will see.

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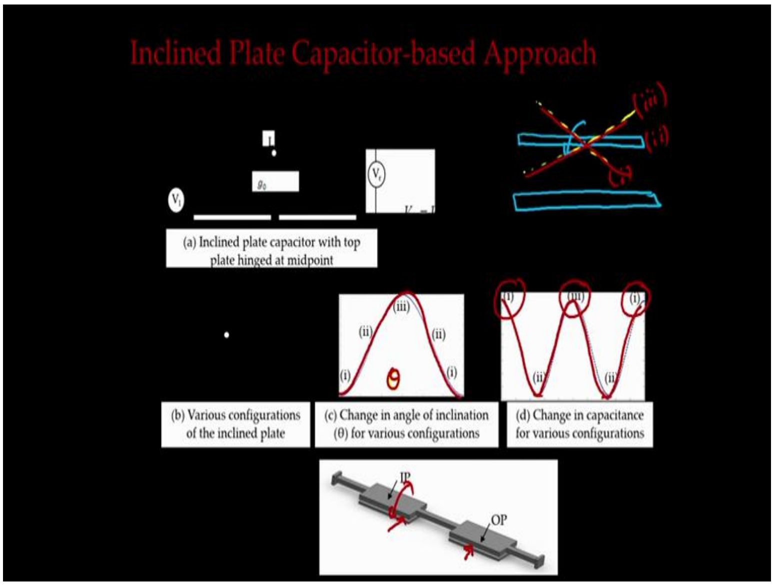

And let us see, I think the background here while we click all of them, alright. So, this one I think you are not able to see something here because black and white there is a problem. What we will actually need is that if you have a let us say a parallel plate thing like this here is in electrode and this one can tilde about this point. Let us call this position one and when it tildes, when it tildes let us say, let me choose a bright color when it tildes like this capacitance would increase and go to some value which is a very high and then when it tildes this way it is symmetric it will be still the same thing.

What you are doing here if this is the angle, so this is the angle this is the angle which goes from 1, 2, 3, to 1, capacitance what will do is 1, 2 and then 3 and then 2 and then 1. So, again 1 cycle here became 2 cycle, this is 1 and let us call this 2, let us call this 3, at 1 and I think it should be like this, I think this should be in 1 and this should be 2. At 1 and 3 we have the same capacitance because inclined we will have same frequency whether this way or that way, in between it will have a reduced capacitance where as the motion if you see the theta it can go to 1, 2, 3 to 1 whereas, this goes 1, 2, 3, 1 in this fashion. So, we can put this tilting over here with electrode underneath as it is shown. So, we can get a very easy frequency doubling, not cycle doubling because they can go at a very high frequency.

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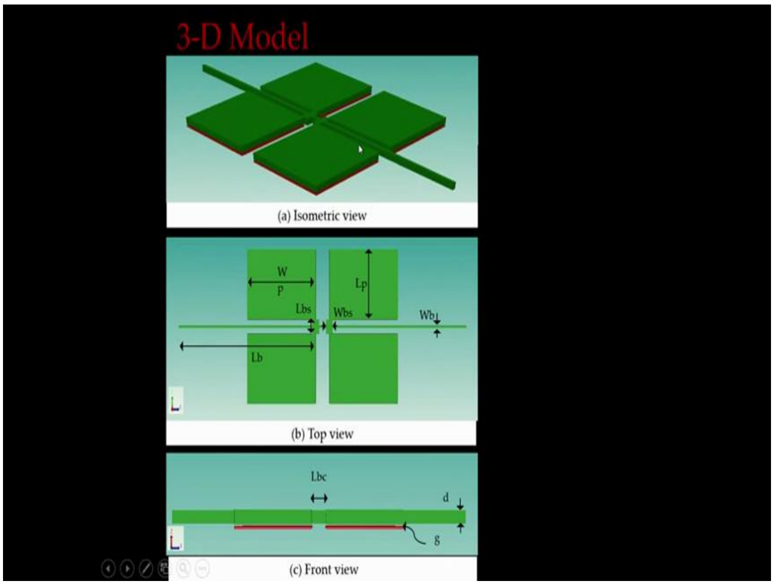

Here is one a 3D model where this flux can move this way that way to a transmit and this is just a analysis model in coventorware software and you can see how from the input to output how things change.

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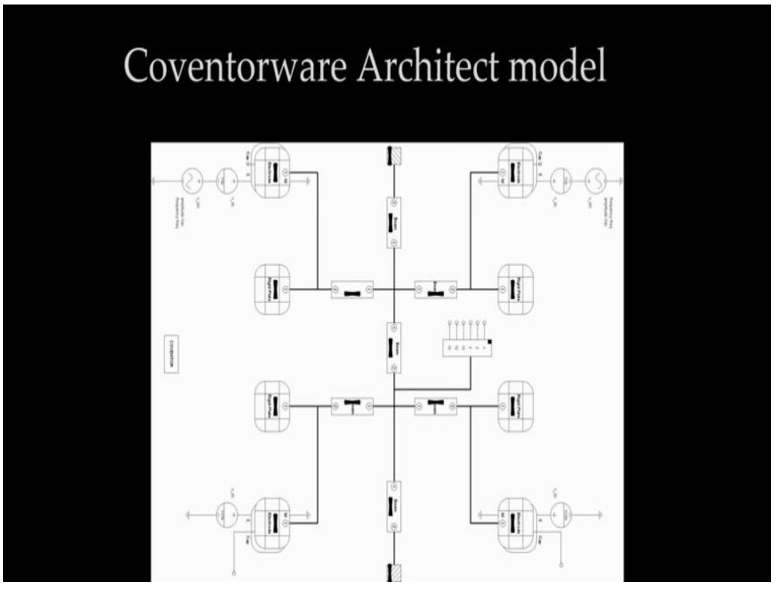

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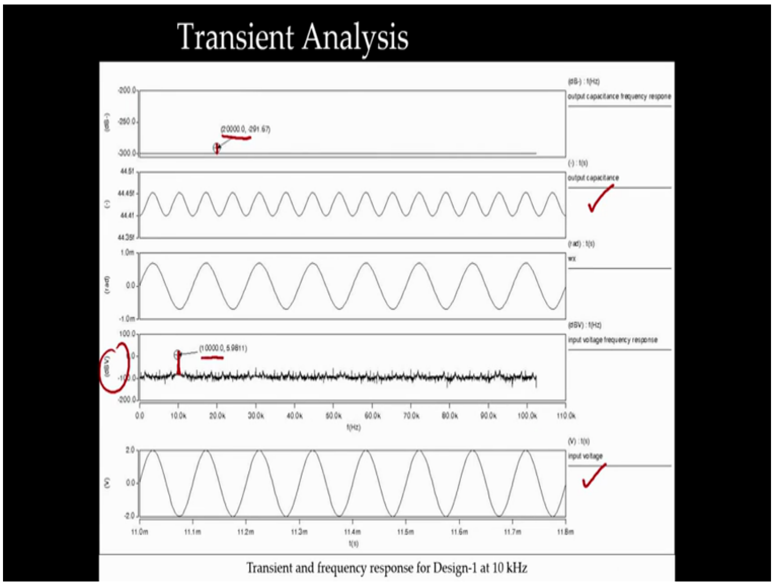

The input is here and output capacitance is here, where the frequency is doubled for the signal and in fact, if you do the db the frequency response you can see that this input is in this case 1 lakh and the output is 2 lakhs there is a peak there everything else is, you know frequency response is very small, db scale it is very large db to 300 to 50 and here is 100. So, we can see that we can use a little compliant suspension to do the frequency translation.

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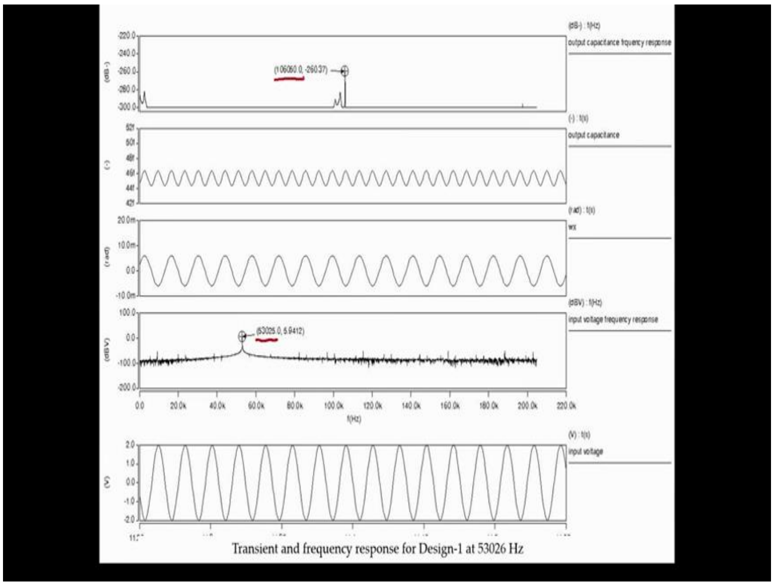

And here is another example where input is a 53000, output is 106000, frequency doubler this one is.

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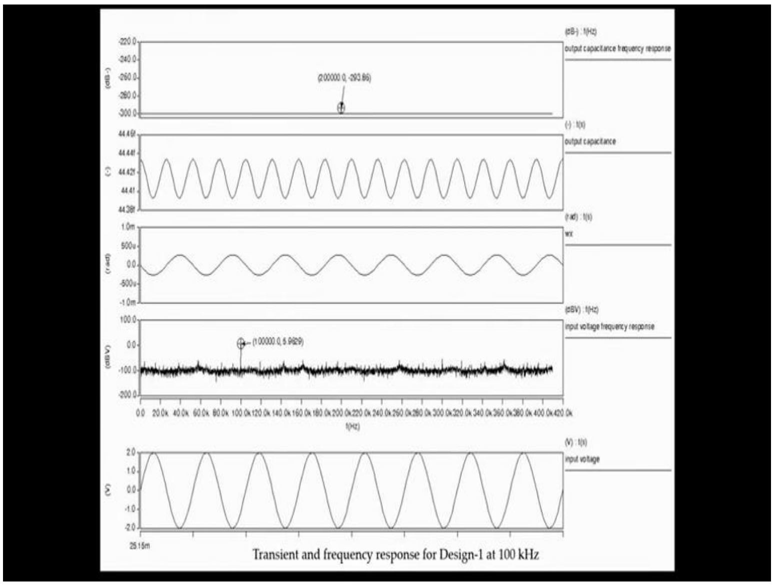

The other one a different design each of them have this features, there is a planar version of this, this has to tilt out of plane, but what about thing is that just move in the plane much better from micro electromechanical systems. So, we have a planar design.

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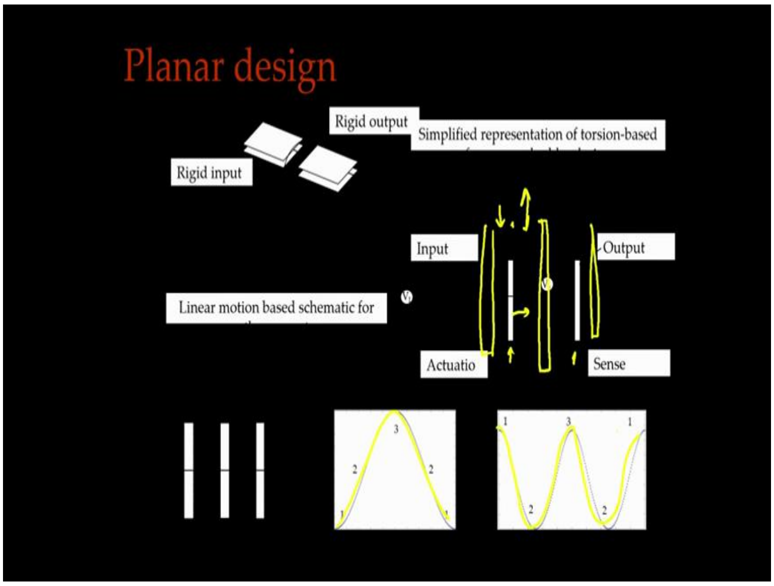

So, again here there is some problem with the colors, but let us actually discuss the principle. So, here imagine that there is one electrode and another electrode and another electrode let say these are fixed and these are the moving once when this one moves like this one side there is a capacitance another side there is a capacitance, 1 increases, other decreases.

When this goes back and forth the motion goes like this and the capacitance once again goes like this because when you have something in between when you go this way and come back to this way capacitance would have changed twice because the symmetry that exists. So, when it goes like this capacitance here will increase other will decrease, but if I go like this here it will increases other decreases, if you take that electrically when you go once like this capacitance would have changed twice. It is a planar design, very simple as we will see in the next slide.

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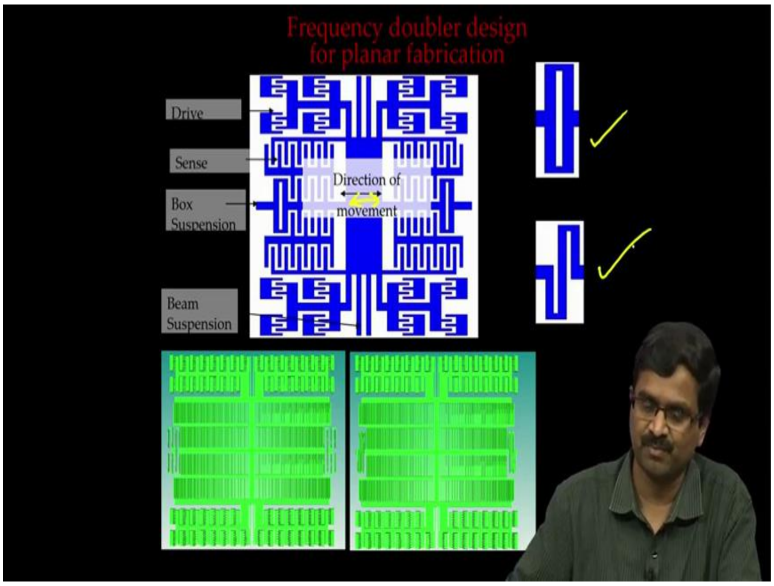

When you move it in this direction back and forth, capacitance that is there is going to change at twice the frequency which can be taken as the output. So, that is also a compliant suspension that gives you the frequency translation feature. So, these are all different suspension these are the key things here, we have to have it proper suspension.

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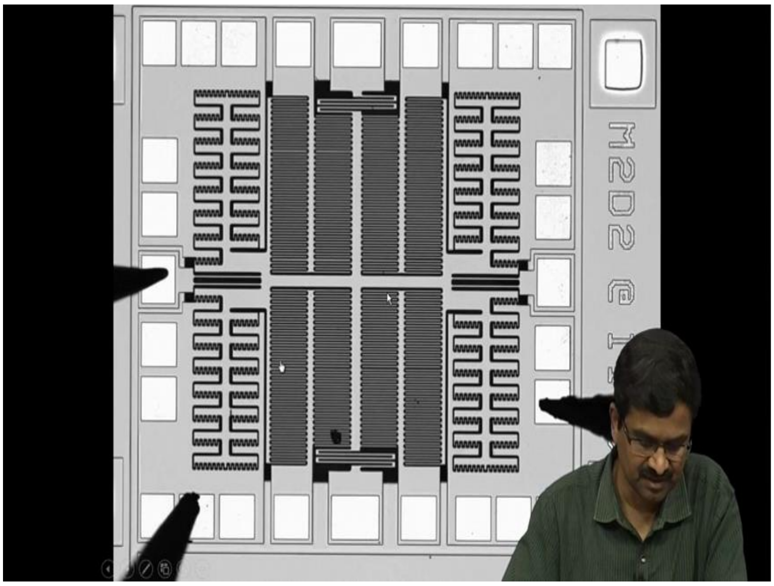

And this is the micro fabricated frequency translator. So, these are tiny beams that you see, these are all 5 microns and the gaps are also 5 microns, they can made even 3 microns, 2 microns, these are the probes that you see, that is where you put them into electrical power supply and this will start moving and input output if you measure will have frequency doubling all because of suspension, there is lot of beams, the parallel beam suspensions are over here and this side.

And this is actually supposed to be a movie, let us see if we place, it moves a slight noticeably, may be the movie file is not there.

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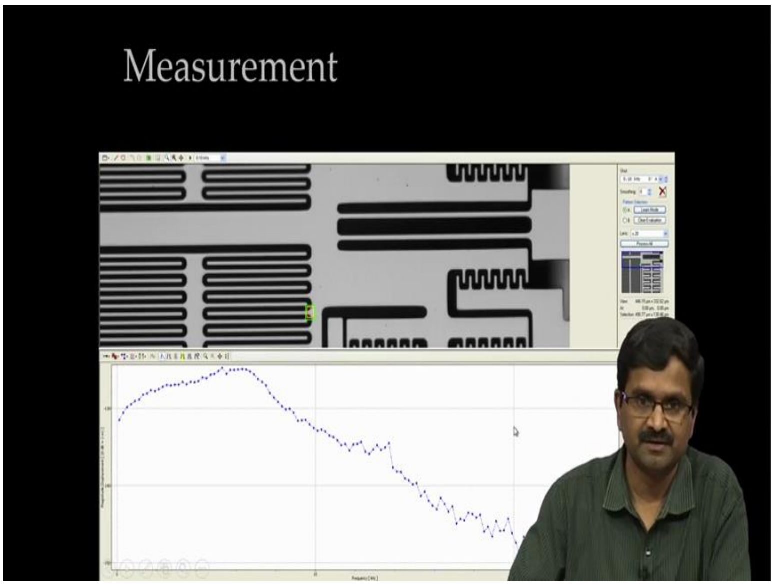

We measured it and it actually works like a the frequency doubler and then move it on to frequency quadrupling also that is f comes and for f goes out as output.

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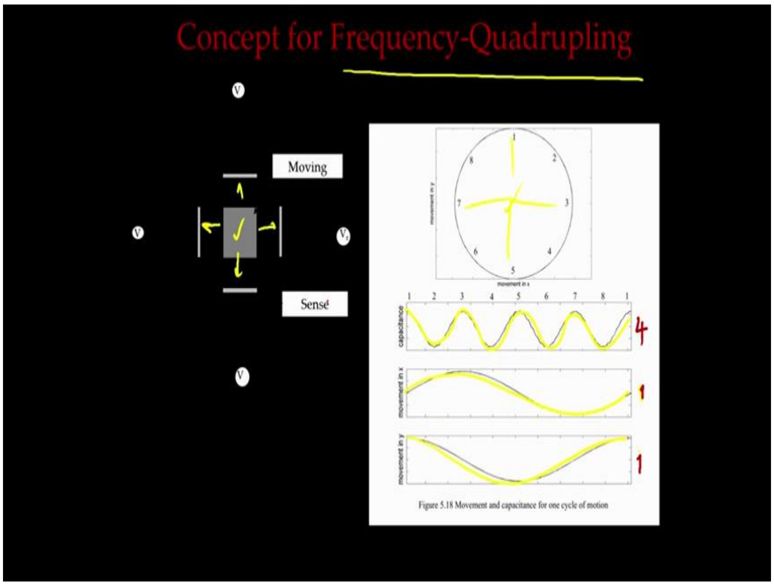

Here what we need to do is we have to have a mass actually move symmetrically with respect to 4 electrodes in a fashion like this, it moves this way that way combination, if we do it this what is shown as a clock 1, 2, 3, up to 8 as the mass moves you have symmetry and all four sides. So, input that is a wide movement at one frequency, x movement also at the same frequency output will be 4 times. Here it is only 1 cycle 1 cycle, so let me change colour one cycle, one cycle here you have 4 cycles.

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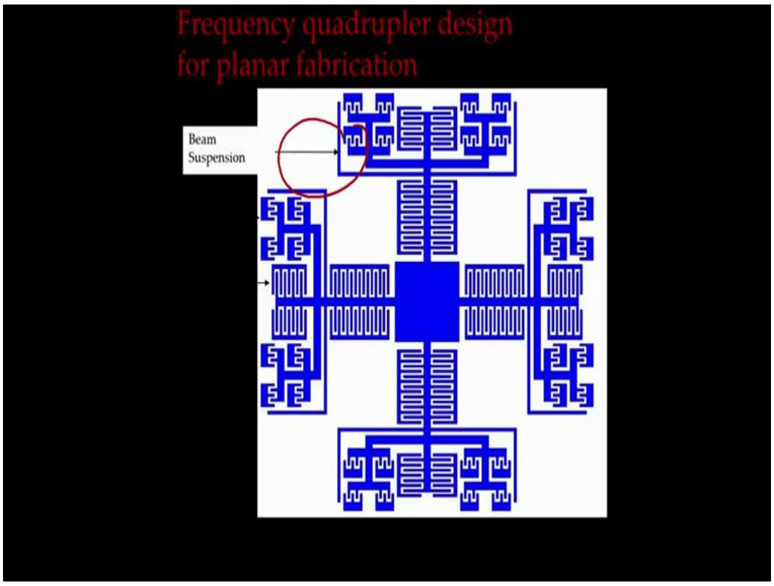

That is can be done very fast with one moving at the sensing we can actually make a frequency quadrupler which is the mass looks like this for it and again beam suspensions are the keys here, the important once. And this is the mass layout for the frequency doubler and Quadrupler

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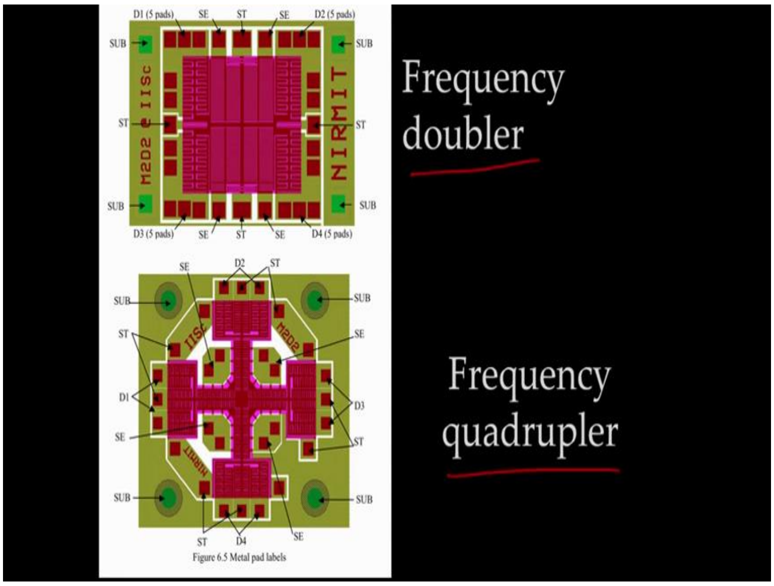

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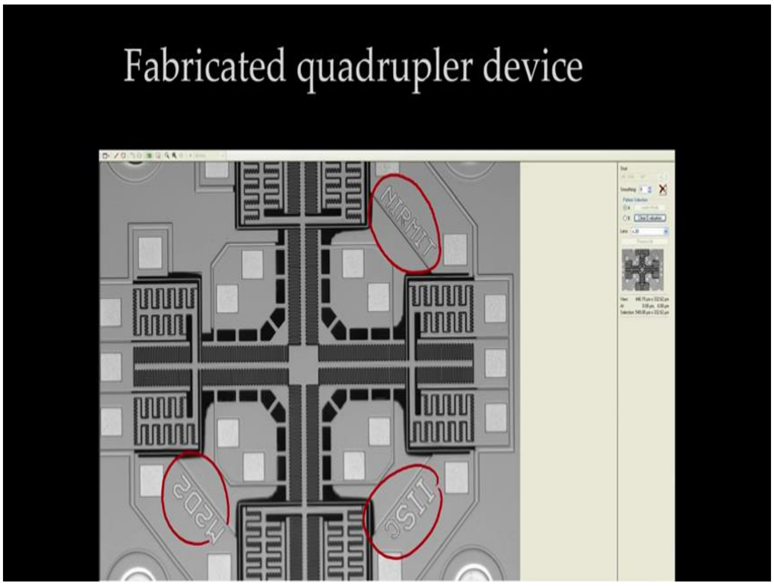

And this is the Quadrupler micro fabricated 1 and Mister Nirmit have actually new printed his name on it along with IISC and in our lab M2D2.

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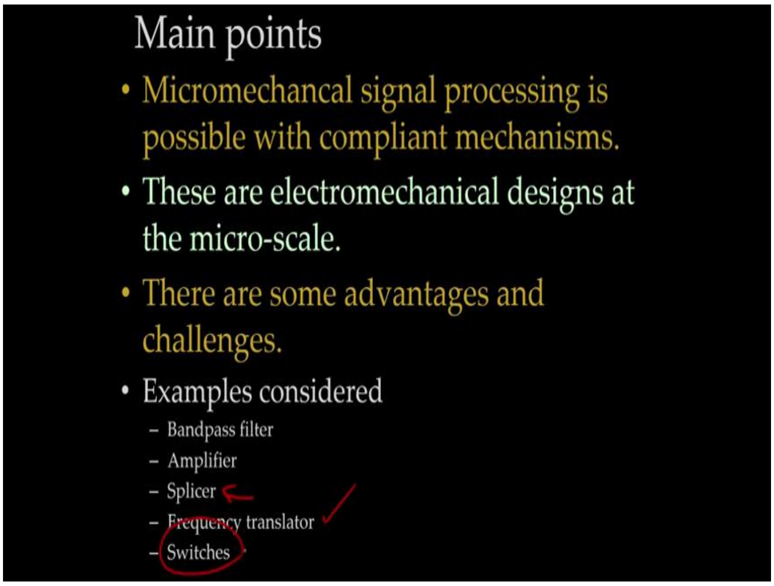

To summarize what we have discussed is a way of doing signal processing using compliant mechanisms or compliant suspensions and it is not a surprise because they are all electromechanical designs they are quite amenable for micro scale and they have better performance than their electronic counter parts. And there are lot of advantages, but also lot of challenges to make them, one should actually do very careful electromechanical design when we use compliant mechanisms that we will discuss at length. We have discussed the micronewton force sensor as well as micromachined accelerometers and micro grippers.

We considered examples in this lecture on Bandpass filters, amplifiers of force and displacement and I did not talk about the splicer, but this has to do with the one of the suspensions I showed in the previous lecture where x and y motions are decoupled. So, that particular one, let us look in Grover's. That is for the proof mass we provide x motion and y motion and there are 2 output ports where whichever way the proof mass is moving x and y combination it is moving the x one will pick up only the x motion, y point will pick up only the y motion that is like splicing a signal.

A signal comes with let say 2 components. So, you are taking of one component another component mechanically. So, we can do the frequency up and down and you can also pick out different components of motion separate them out. So, that is a splicing function we talked about frequency translator and then switches we have mentioned once in one bistable phenomenon lecture, we talked about switches. There are number of applications switch is also a very important signal processing element and that can be done very well using micromechanical switches and once again compliant mechanisms become useful there because of this bistable nature that is very easy to end out compliant mechanisms with.

Thank you.