Semiconductor Optoelectronics
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Lecture - 37
Vertical Cavity Surface Emitting Laser (VCSEL)

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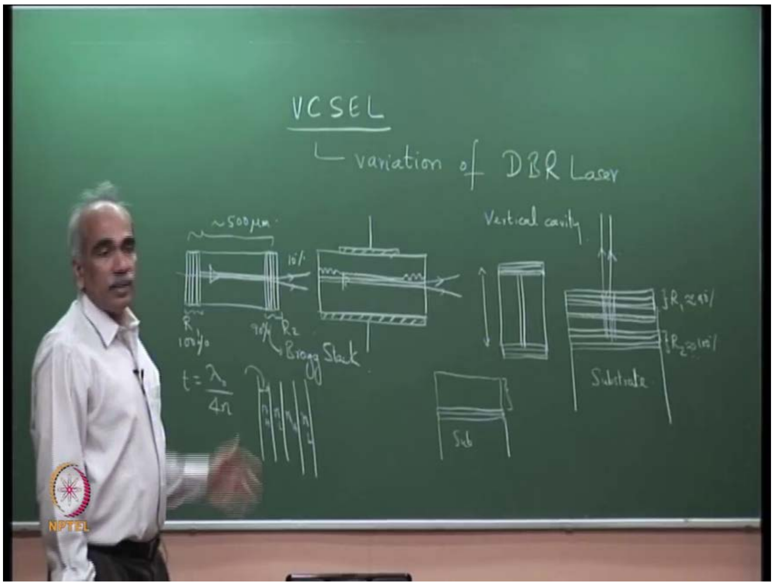

So, today we will discuss about vertical cavity surface emitting laser. This is the variation VCSEL - vertical cavity surface emitting laser, we can think of this as a variation of DBR laser. In the last class we discussed about DFD and DBR laser, DBR laser, distributed bad reflector laser. So, recall the DBR structure, here is the active region and there are corrugations here, that is periodic, periodic structure. The frequency's selective periodic corrugation is there and this is the DBR and I had discussed that this was basically you have a cavity here. The Fabry-Perot of this came up, that if we can put frequency selective layers here, frequency selective reflection layers, each layer is of thickness lambda by 4n, so these are the Bragg stacks, so the Bragg stack, that is one high index layer. So, if you want to expand this and see, these are basically high, low, high, low, so n high, n low, n high, n low. And thickness of each layer here, thickness here is t is equal to lambda, lambda is the wavelength you want to select, so lambda or lambda 0 divided by 4 times n. The thickness of each layer, water wave length thickness, each one of them, so that forms a reflector for this wavelength, lambda 0, so this is the basic idea from which the DBR structure had come.

Now, if you look at this, see the origin of the VCSEL, if I rotate through 90 degrees, just rotate through 90 degree, so what we will have is the structure like this. The cavity, in this case the cavity, mode is going back and forth in this direction, so the cavity is horizontal, the cavity is horizontal, the mode is going back and forth. If I rotate this, the cavity is vertical, so this is vertical cavity, just rotate it through 90 degree.

However, typical length here in the DBR or this structure is approximately, this length is about 500 micrometer. In a normal Fabry-Perot laser, the length is normally about 300 micrometer and in, in DFB and DBR, it is 500 into 100 micrometer, typically between 500 and 1000 micrometer because you need relatively longer length for getting sufficient feedback. If the length is very small, the feedback is not sufficient and that is why, normally, the length is more than 500 micrometers. So, if you take this structure, even if you take 300, this height is very large in the sense, if you want to fabricate from a fabrication point of view, you will always start with a substrate here.

Then, whatever layers that we want to deposit, repeat actually, deposit whatever thickness that you want and then if you wanted this thick layer, here it is normally not possible by epitaxy to grow layers thicker than 10 micron by epitaxy. Normally, you can grow layers 0.1 micrometer, 1 micrometer, 2 micrometer, 5 micrometer. But normally, it is not possible to grow thick layers, which means, in this structure if I want to grow a vertical cavity, that is, I want to make a laser starting with substrate here, you deposit the Bragg stack here, the Bragg stack for reflection and then you deposit the active medium and then you have again Bragg stack for reflection. This is, in principle, it is fine. The reflectivity, there are mirrors of reflection, R 1 here, R 2, please see, this is R 1, R 2, which stacks for the reflectivity. So, R 1, R 2 and this is the active medium.

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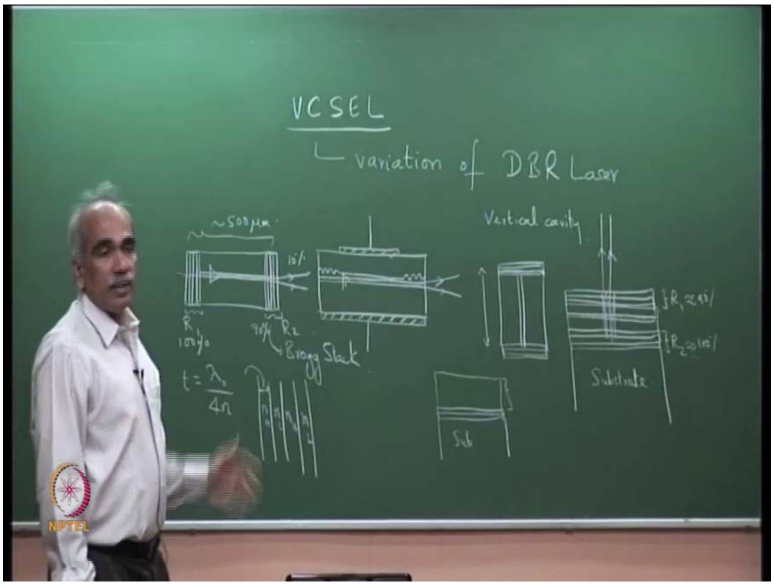

So, you, in the active medium if you, you need double hetero-structure, there is a double hetero-structure here and what results is the vertical cavity surface emitting laser. Why is it surface emitting? Now, because in this case, light was coming here, in all these light is coming from the edge; in all these lasers, light comes from the edge. But in this case, (( )) laser substrate, then this is, light is building up in this direction and therefore, light is coming here from the surface. The cavity is vertical, light emission is from the surface.

Please recall, a normal laser reflectivity at one (( )). If you are depositing yourself, you want this to be 100 percent. Let us say, this is 100 percent and this is 95 percent or 90 percent. These reflecting layers you see, this is no more edges. It is reflecting layer, which is deposited. So, you have made reflectivity 100 percent, reflectivity 90 percent, which means 10 percent of light is coming out of cavity. So, I have just rotated this and made this cavity here. So, you have made reflectivity nearly 100 percent and reflectivity nearly 90 percent, let us say, then 10 percent of light is coming.

This is the structure, so vertical cavity surface emitting laser, so it is vertical cavity on the substrate. They have grown and surface emitting, this is the vertical cavity surface emitting laser. There are several design considerations involved, what kind of reflectivities do we need? So some numbers if we put, it would be more clear.

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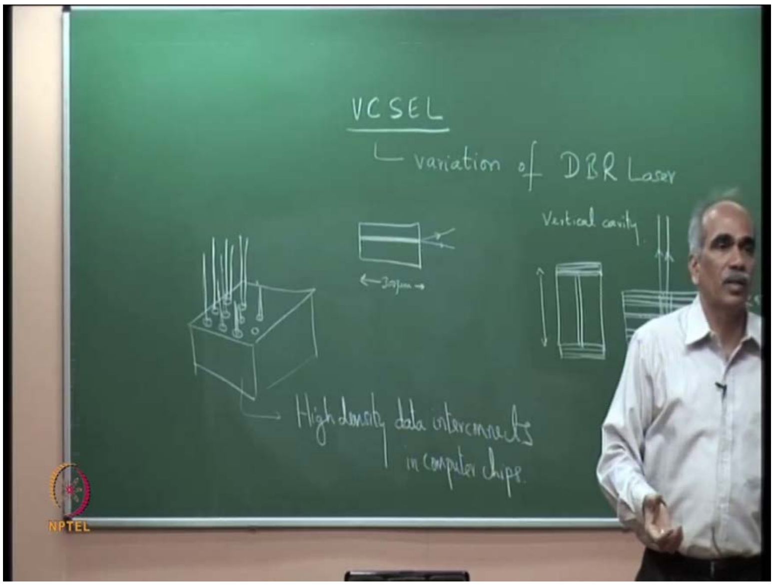

So, let us see a little bit of analysis there, but the basic idea of realizing a vertical cavity surface emitting laser is straight forward. It simply is a variation of DBR laser where you have rotated the cavity through 90 degree, so that output is coming from the surface. Why do we want such a structure? Because, then on a chip like this, on a chip you can grow large number of lasers all emitting to the top upward from the, this is top view I am showing, so all these giving light like this. It is an array of vertically emitting from the surface, lasers emitting from the surface, you can make an array of lasers. There are several applications of such arrays including pumping to other lasers. For pumping other lasers you can make array of such lasers and today there are lasers, which can give up to 1 watt in this structure. Initially, vertical cavity laser were made, output was very small, 10 of microwatt, but today there are hundreds of milli watt from each element is possible. So, the technology has advanced so much.

Now, some numbers I want to discuss, so first the motivation, why go for this? The normal semiconductor lasers, as we, although they are very small and compact compared to bulk laser, like helium, neon, laser or NDR lasers, very small, very compact about 300 micrometer length or 500 micrometer length. This is very large compared to micro-electronic component.

Microelectronic components are 1 micron, these are, these are very large, very bulky. It is alright for communication, from the communication point of view. From an optical communication point of view such size of devices is fine because you have some sources; you may need in a DWDM system. You may need, let us say, 64 or 128 such lasers, they do not take lot of space. But if you want millions of laser, as I mentioned, one of the most important application, which has come up is high density.

So, high density data interconnects; high density data interconnects in computer chips. It is very important because it is also very important because this lasers can be modulated at tens of gigabits per seconds speed directly; you can modulate the speeds of tens of gigabits and you can have a million component on 1 centimeter square. You can imagine the data density, which is possible with such a system, whereas these ones, if you want to put a million components, it is very bulky. For communication it is ok because you need one transmitter, which may have tens of laser diodes, but for high density data interconnects it is a primary application for which VCSEL have been developed alright.

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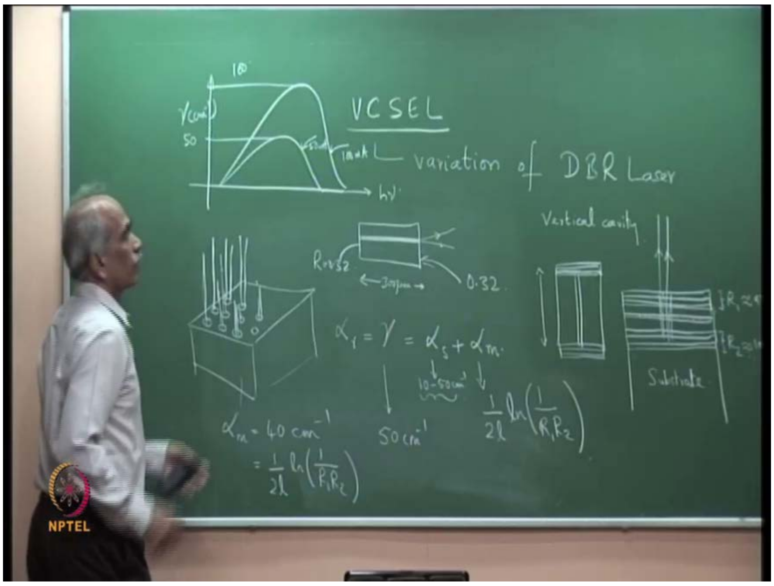

So, I come to the numbers, I come to some numbers. In normal laser, this R was 0.32; (( )) ends reflectivity of 0.32. You recall that we had an expression - the resonator loss must be equal to gain for it is an oscillation, steady state laser oscillation, and resonator loss is given by alpha s plus alpha m, two components, one mainly due to scattering and diffraction losses and second due to mirrors. So, this mirror loss is 1 over twice l into l n 1 over R 1 R 2 and typical gain profiles if you see, the gain profile that we had, recall the gains that we had, this is gamma versus energy h nu or lambda for different values of delta n or current. So, I can write in terms of delta n or current, let us say, 50 milli ampere is the current and this is for 100 milli ampere. Typical numbers, that we have here are, let us say 50 gamma centimeter inverse.

Let us have a field for the numbers, 100 centimeter inverse and so on. Just I am taking some numbers, so this is h nu or wavelength and then this is the gain curve. So, if gamma is 50 centimeter inverse here, 50 centimeter inverse and doing some example calculations, you see the importance why alpha s. I had mentioned, that typically this is in the range 10 to 15 centimeter inverse; typical numbers for alpha s is in this range. If I take the lowest value here 10, then alpha m can be 40 centimeter inverse.

Please see, I am considering the particular example of a particular laser, you are sending it power current of 50 milliamperes and the peak wind coefficient is 50 centimeter inverse. And if I assume, that alpha s is 10 centimeter inverse, then alpha m should be 40 centimeter inverse. So, alpha m is equal to 40 centimeter inverse. All these numbers are typical numbers and remember, that alpha m is equal to 1 over twice l into l n 1 over R 1 R 2.

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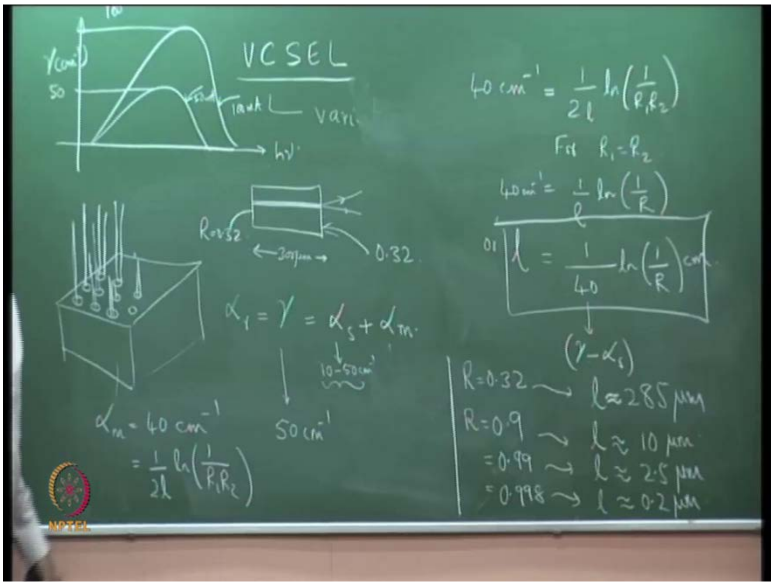

Let me continue with the calculation here, this is a very important example because what I am, giving, going to do is to give you an answer why did we take this 300 micron. In one of the classes I gave you an answer why this thickness of the layer was 0.1 to 0.12 micron, now I am going to answer why this was 300 micron. It is not, you are not just taking numbers, there are reason for every number, right. So, alpha m here is equal to, so 40 centimeter inverse is equal to 1 over 2l into l n 1 by R 1 R 2.

Assume, that R 1 is equal to R 2, assume that R 1 equal to R 2, for R 1 equal to R 2 what will this be? This will be whole square, so l n, so 2 2 cancel, this will be equal to 1 over l into l n 1 over R equal to 40 centimeter inverse or l is equal to 1 over 40 centimeter, here 40 into l n 1 over R centimeter, this 40, what was this 40? It was actually gamma minus alpha s. If you want to write formula, it will be 1 by gamma minus alpha s into l n this. In my example it was 40; actual formula is 1 over gamma minus l s into l n 1 by R. If you substitute value, if you put R is equal to 0.32 and substitute in this, you will find, that l is equal to 285 micrometer. The point is, so if you need 40 centimeter inverse is gamma minus alpha s, then length has to be 285 micrometer.

If R is in this range, if I increase R what will happen? If I increase R, so it is 1 by R, therefore this number is decreased and therefore the l will decrease. So, if I put R is equal to 0.9, that is, 90 percent both ways, then you will get l. Please check this number, approximately l is equal to 10 micrometers. If I make R is equal to 0.99, l is nearly equal to 2.5 micrometer. If I make R is equal to 0.998, almost approaching 100 percent reflectivity, l is equal to 0.2.

What, what do this calculations tell? You can have thickness of the gain medium. l is what, length of the gain medium. If I want to reduce the length of this gain medium, the reflectivity must be high, otherwise alpha will, grown up alpha has l in the denominator. So, if your l reduces, alpha will increase unless it increases this. If R comes close to 1, note that R is equal to 1, l and 1 is 0, so if R comes close to 1, then you can reduce l, otherwise you cannot reduce l. So, in a normal laser, because this was a 0.32, you require at least 300 micron, that is, that much length of the gain medium to make up from the losses from the resonator. If reflectivity is 32 percent, it means, 68 percent of light is lost from the resonator. To make up for the loss you need length of the gain medium long enough, length of the gain medium, so that the light is getting amplified to make up for the losses. So, if the reflectivity is higher, then you can reduce the size.

In the vertical cavity structure, as I mentioned, that it is not possible to have such thick layer of active layer, so you want to have a small active layer thickness, which means, the only way you can do is by increasing the reflectivity. This is exactly the idea that in vertical cavity surface emitting lasers, normally people use reflectivity in this range, 0.998, then you can have an active medium whose thickness is only 0.2 micrometer. Do you follow? So, in this this example we answer why it was 300 because it was simply edges. We could not have gone less than that, and how to go this small thickness? By increasing high reflectivity, and therefore you see now the structure of vertical cavity surface emitting laser. We will see the structure here.

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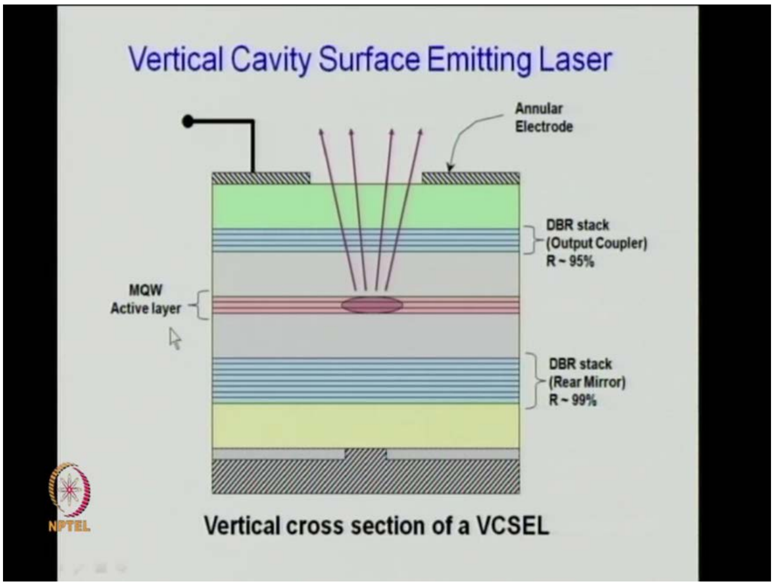

So, here is the vertical cavity surface emitting laser please project. This, so there you go, you can see the structure clearly. The structure comprises of, you see, this is the substrate here and you have the Bragg stack here, which provides reflectivity, high reflectivity and then here is the active layer. This active layer is basically a double hetero-structure, here it is written MQW. I will make a statement, that today most of the lasers have their active layer as MQW structures, multiple quantum wealth structures. In double hetero-structure, the active layer is this based multiple quantum wealth structures. What is this multiple quantum wealth structures we will see in the next class, but this, our active region and outside, these two are cladding regions. This is the active region, which forms the double hetero-structure and here is the, and here is the reflectivity provided by the upper layer.

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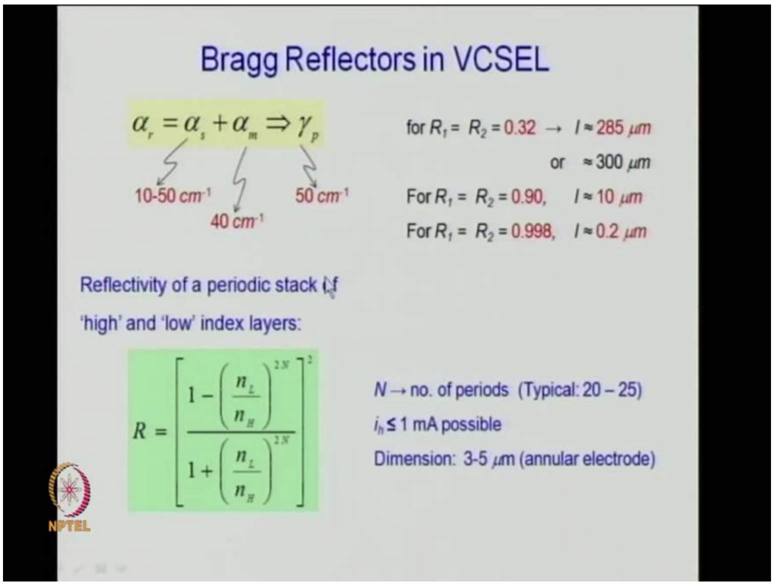

So, that is the Bragg stack, that is, a Bragg stack here. So, this is the upper Bragg stack and the other one is the lower Bragg stack. So, we have the basic structure

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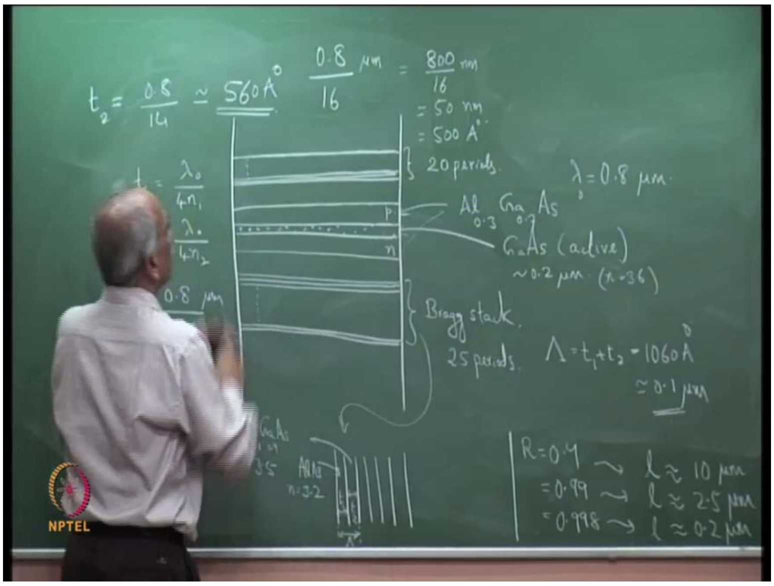

So, let me draw it here. You have, because there is one more layer in between it is mixing, I will show that you have the active layer here, which we normally show by dotted line. Outside this is the cladding region so which is the one, which forms a double hetero-structure, a low band gap material sandwiched between high bandwidth materials. So, in simple term this could be, for example, gallium arsenide laser, this is gallium arsenide active layer, so active. So, typically, the thickness is 0.2 micron-meter, outside is the cladding layer, this is gallium arsenide. Let me see this, aluminum gallium arsenide l.3, gallium 0.7 and arsenide. So, both are aluminum gallium arsenide here, so this is p, this is n and this is p and below this we have lower Bragg stack.

So, here the Bragg stack, so number of layers here, typically people use about 25 periods here, so this is the BDR Bragg stack. For example, this Bragg stack may comprise of, let me show here, the Bragg stack will comprise of high, low, high, low layers. So, this is, for example, this is aluminum arsenide, aluminum arsenide, this refractive index is 3.2 lower refractive index and this one is gallium, aluminum. So, aluminum 0.1, gallium arsenide, so gallium 0.9, aluminum 0.1, gallium 0.9, arsenide. Remember, that gallium arsenide has a refractive index n nearly equal to 3.6 and aluminum arsenide has the large band gap, refractive index is 3.2, this is approximately, n is equal to 3.5. This value here is n, this is n, so what we have is low refractive index, high refractive index, low, high, low, high.

And how do we choose the thickness? If I call this as t 1 and this thickness as t 2 here, then t 1 is equal to lambda 0. Let us say, the laser is gallium arsenide, laser, laser is lasing at lambda 0, is equal to 0.8 micron-meter, say for example, laser wavelength is 0.8 micron-meter, then I have to choose the thickness as, such that lambda 0 divided by 4 times n 1 t 2 is equal to lambda 0 divided by 4 times n 2. I am putting some numbers so that you get the feel for the thickness of the layers. So, what is lambda 0 here? Lambda 0 is 0.8, so t 1 is equal to 0.8 micro-meter divided by 4 into n 1. n 1 is 3.2, 3.2, so this is 4 times 1 by 16, so this is nearly equal to 1 by 16, is approximately equal to 0.6, 0.6 micron-meter, 0.06, 0.06 micro-meter, that is, approximately 600 Angstrom, the thickness of this layer t 1. Similarly, you calculate t 2, substitute 3.5 here and you will get t 2 nearly equal to 500. Let me just see, this is 4 times 3.5, 14, so 0.8 by 14, 0.8 by 14

Student: (( ))

Sorry

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One second, this is nanometer or micron-meter, 0.06 into 10 power, so this is, wait, wait, wait, not nanometer, right. It is not nanometer, just a minute, 0.8 divided by 4 into 34, 16, this is micro-meter, which is equal to 800. So, multiply 800 divided by 16 nanometer, so this is equal to 600, so 60, 60 something nanometer, that is, 600 Angstrom, 5. So, this is, I should have written 16, so exactly 500, right. This is, this is nanometer, so 50 nanometer, so this is equal to 500 Angstrom. So, it is not, in this case it is exact, so I am sorry, so please correct this, 0.05 micron-meter, this is 500 Angstrom. Anyhow, the order was right, but it is good you interrupted, that we have got the correct value now, that is, 500 Angstrom, alright. Similarly, please calculate, for the other one I have used the right value, so this is t 1 and t 2, calculate this t 2. So, t 2 is equal to 0.8 by 14, so this will be approximately, 500 is 70 and again 10, 5, 65, 60 Angstrom.

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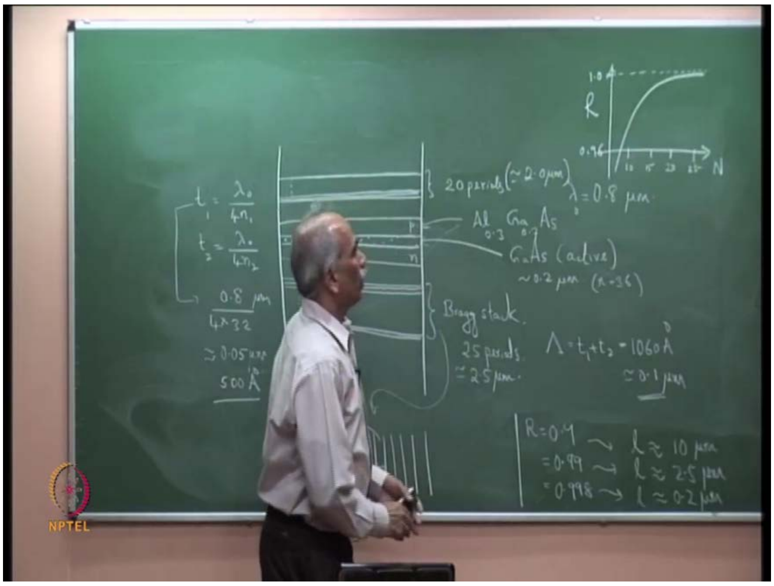

Now, why did I write this? So, one is approximately 500 Angstrom and another is 560 Angstrom. So, if you had lambda, the period, please see the period here, which is lambda is equal to t 1 plus t 2, which is equal to t 1 plus t 2 is equal to 560 plus 500 is 1060 Angstrom. So, 1060 Angstrom is 106 nanometer or equal to, nearly equal to 0.1 micrometer is the period. So, typically, people use here 25 periods and for the upper Bragg stack here, I also have an upper Bragg stack here, which is there in the diagram. So, this is the upper Bragg stack, 20 periods, so DBR upper Bragg stack, approximately 20 periods. 20 periods means, this will come out to be about nearly equal to 2 micrometer thickness.

See, why I have put all this number is, you get an idea what kind of thickness, otherwise if you just write the structure like this, you have no idea what is the actual value and what kind of thickness here. This is approximately 2.5 micrometer and below is the substrate. Substrate is generally about 50 to 60 micrometer; on that you have Bragg stack, 2.5 micrometer, 25 periods. Larger the number of periods, larger will be the reflectivity. Please see this, the reflectivity of the stack is given by the next slide there, shows you the reflectivity, alright.

Let me, what will I erase? If you plot this reflectivity, I am plotting reflectivity, reflectivity is given by the formula there, 1 minus n low by n high to the power 2 n divided by 1 plus n low by n high to the power 2 n whole square. So, that is the reflectivity of a Bragg stack, a periodic structure, where N is the period, capital N is the period.

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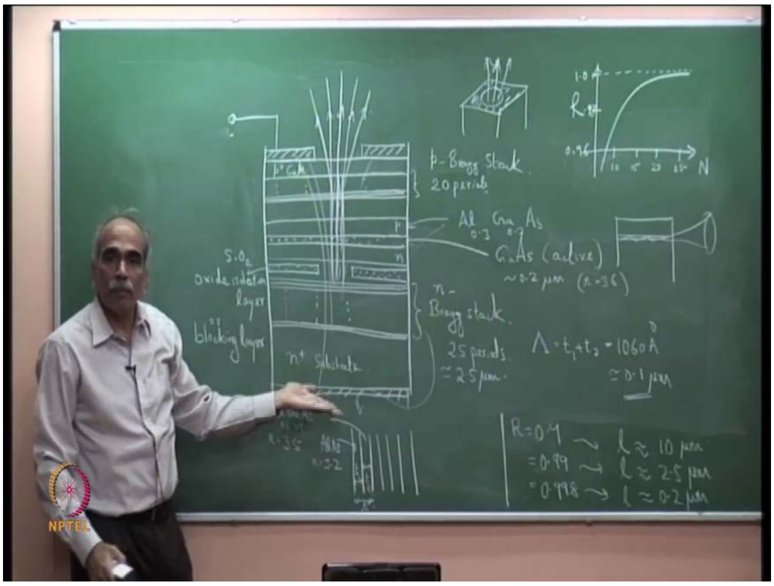

So, if I plot N here, what is reflectivity? Typically, the reflectivity varies like this, so this is 1, 1.0 and here it is approximately 0.96. This is 10, 20, 25, 15. So, what I have plotted is, let us see, see this graph clearly, reflectivity versus, this is 0.96, this is 0.98, 0.98, 0.98. So, by taking 20 to 25 period, so reflectivity is approaching 0.995, 0.996, 0.998, that is why we take 25 periods here. So, this reflectivity approaching almost 100 percent and this is almost 99.5 percent. So, the structure, now I hope the structure is getting clear, so let us go back, see the structure there in color.

This is the active region, cladding region, the Bragg stacks, these are the Bragg stacks, I have written 25 Bragg stack here, 25 periods here is called the Bragg stack, the stack of layers and above this you have the annular electro and window, window for the laser light to come out. So, this is the metallic electrode, the contact positive, so this is p plus gallium arsenide. So, this is the Bragg stack, which is n Bragg stack and this is p Bragg stack, 20 periods and here is the p plus and this is n plus substrate.

So, this is the longitudinal cross-section, what is shown on the screen is vertical cross-section of the basic. If the figure is there and I have drawn the same thing, so you can see how much is this total height on top of the substrate. This is 2.5, this is about 1 micron, 0.2, 0.61 micron, this is 2, so 3.5, 3.6 of the substrate. So, substrate is below 50 to 60 micrometer and this is an annular electrode. So, please remember, that if you see the three-D view, then it should have an annular electrode. I, unfortunately, I did not have diagram, which showed a three-D view, so here is the, so the light is lasing here in between, it is building up here, the light is building up here and coming out of the surface. There is the bottom electrode here as well (( )).

You can imagine what is the need for this, we have discussed this in the case of LEDs, surface emitting LEDs. Same reason, unless you block this, the carrier should go here. So, this is blocked, this is SiO 2, usually SiO 2, this is oxide layer, blocking layer, then the carrier should go like this and so that light is directed here because you want to come out light here. If this is not here, the carrier will flow here, so that is why this layer used isolation, oxide isolation layer or blocking layer, so that light is generated in the central portion.

And this is top view, the light comes from here, so usually the electrode is annular and output that you get is a circular one of the important advantages of VCSEL over the fibrotic laser. We have discussed the characteristics of the fibrotic laser. The output is oval in shape; the output is oval in shape because it is highly confined in this direction, less confined in this direction, so the diffraction leads to an elliptical shape here in the output.

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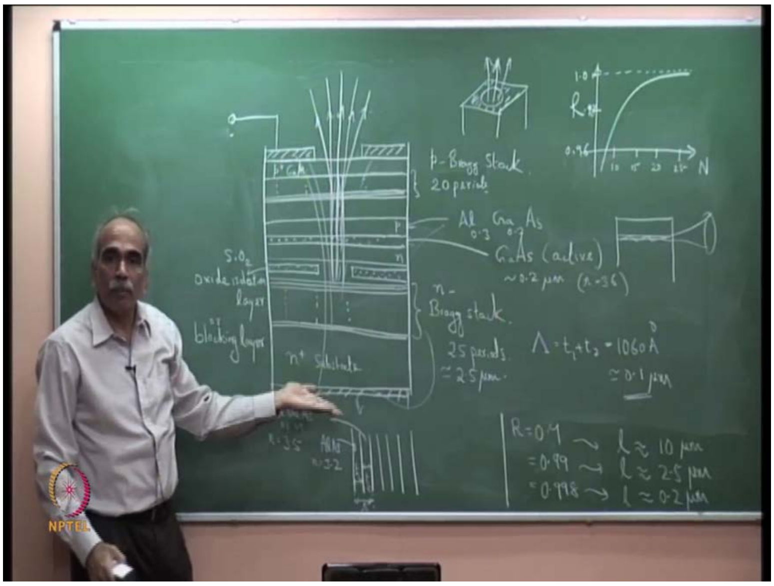

Whereas, in this case it is the circular cross-section beam, it is not, it is confined identical because you see they are all layers. So, it is the plain wave going up and down, it is only wave, there is no wave guidance, there is no optical wave guidance here because it is light is travelling perpendicular to the layers. In this case, there is optical wave guidance, it is like this, therefore the beam when it comes out diffracts. Here, it is light is going just up and down, there is no optical wave guidance and therefore, the beam output is circular in cross-section.

This also is an advantage. If you want to couple these two optical fibers, the coupling efficiency of this will be much more compared to the coupling efficiency here because fibers have a circular cross-section and therefore, if the beam is elliptic in cross-section, the coupling efficiency will be poor.

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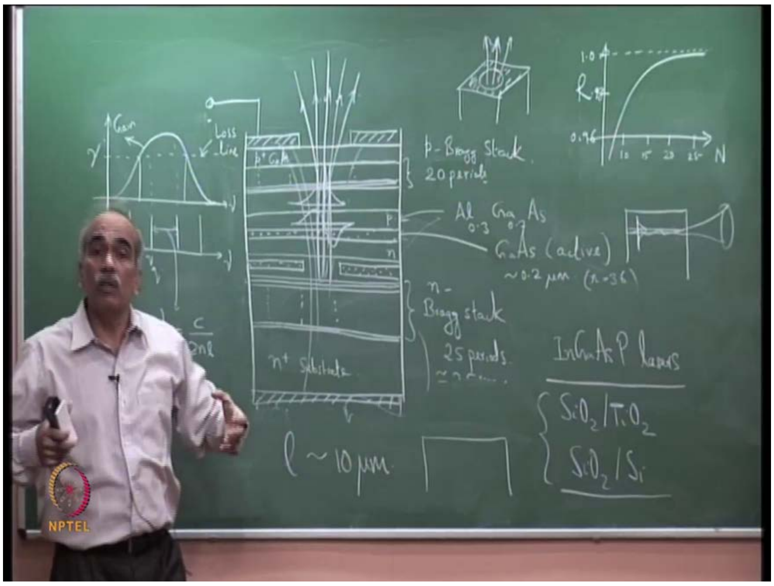

So, I have taken the example of gallium arsenide laser here and therefore, the Bragg stacks are normally used, made up of aluminum arsenide and aluminum gallium arsenide, but in the case of indium gallium arsenide phosphide lasers, indium gallium arsenide phosphide lasers, usually the Bragg stack comprises of SiO 2, TiO 2 or SiO 2, Si layers, alternate layers of SiO 2, TiO 2 and SiO 2, Si layers. TiO 2 is conducting as you know, titanium oxide, tin oxide, oh, this titanium oxide, so it is SiO 2, TiO 2, titanium oxide and SiO 2, Si layers.

But you can imagine, that these are dielectrics, so if we put, in this case you can put, there is no problem because it is semiconductor and this is n (( )), all layers are n (( )), all layers are p (( )), so it is p n junction here. But in the case of SiO 2, TiO 2 layers, this is a dielectric, so how the current will flow? In this case, there are structures where the Bragg stack is limited to the center and current flows from the side, there are special structures. You can see in the literature that the layers do not run from end-to-end here. There the Bragg stack is only in the central region and the sides comprise of semiconductors, so most of the SiO 2, TiO 2, Bragg stacks are realized only in the central portion. There are very special structures where you h deposit only in the central region because in this region, light is building.

One last point is, that the length of the cavity here, so this length we have seen, that is approximately total length is less than, are of the order of 10 micron-meter. Please recall, that this is 2.5 micron-meter, this 2 micron-meter, this is about 1 or 2 micron-meter, which means, the total cavity length is less than of the order of 10 micron-meter. If the length is very small, the free spectral range is very large. Recall, that gain spectrum of the semiconductor is this and the cavity resonances are here, these are the cavity resonances with a free spectral range here. So, in the both the cases the axis is mu, so this axis is frequency mu, this is gain gamma and this is resonance frequency mu and this is the free spectral range, mu f is equal to c divided by 2n into l.

Unlike the case of bulk semiconductor laser, here l is very small, l is the order of 10 micron, which means, mu f, the free spectral range, is large. The separation is large and therefore, normally within the amplification bandwidth, amplification bandwidth is this one, this is the amplification bandwidth because this is the loss line, loss line. Recall the last class, loss line and this is the gain curve, gain. So, within the amplification bandwidth, that is, net amplification where the gain is more than loss, you normally have 1 volt. I have shown in this case, there are two, there appears to be two, but normally, the separation is large enough, so that there is only one longitudinal mode and therefore, usually VCSEL are single longitudinal mode structures. So, this also falls in the class of single frequency lasers just like DFD and DBR laser, VCSEL is also single frequency laser because the frequency is selected here also by the Bragg stack and the cavity is also very small and therefore, the free spectral range is also very large. This leads to a single, usually a single longitudinal mode oscillating in the structure.

There are more advanced structures currently, there are, there are several problems with VCSEL several issues, that when you have a, when you have, when you have to grow a large number of VCSELs on a substrate (( )) this annular electrode, the large number of fabricating annular electrodes on the chip is a problem. But there are methods to overcome them, but that is an issue.

The second issue is in terms of transverse field controls, control of the transverse field. In this case the transverse mode is determined by the optical wavelength, so there is no problem. You know exactly what is the motion? What is the transverse field? In this case, there is no guided mode because it not a wave guiding structure. Therefore, the transverse field distribution of the beam, which is coming, whether this is Gaussian or whether this has higher order modes, this is an issue and there are large effects to control mode profile of the transverse mode profile. More recently people are using photonic crystal structure. The upper Bragg stack comprises of photon crystal structure for controlling the mode shape so large, the considerable advances is still going on in the case of VCSEL. So, we will stop here for the VCSEL and in the next class we will discuss about quantum well lasers.

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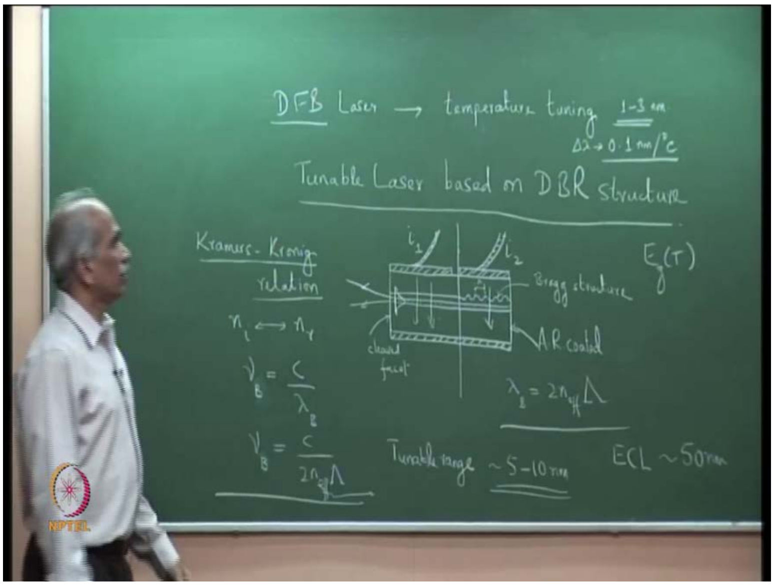

Before I proceed with the discussion on VCSEL, let me discuss the small topic, that is, tunable laser, based on tunable laser, based on DBR structure. In the last class we have discussed about DFB lasers and DBR lasers and also we have discussed about tunable laser based on external cavity and rotating, grating. So, both are forms of tunable lasers. At another structure, which is used us a tunable laser, is based on the DBR structure. So, the structure is like this. Let me draw on the board.

The structure comprises of two segments, this is the active region, the active layer. One segment, the structure has two segments basically in terms of electrode. There are two electrodes, in the cladding the DBR grating is at one end, the DBR grating is only at one end. So, this is the cleaned facet, cleaned facet; this end is anti-reflection coated, AR coated, AR coated. And this is the Bragg structure, which determines the frequency Bragg structure. So, depending on the period lambda, this is lambda, period is lambda, so depending on lambda we have the wavelength, the wavelength lambda b selected will be given by twice n effective into lambda.

So, the frequency, selective Bragg structure is at one of the device and this has two electrodes. Here I am showing, these are the contact electrodes, current i 1, i 1 is current through this and i 1 and i 2 is the current through two independent electrodes. The current i 1 and i 2 can be controlled separately. This is the active region and the current, which is flowing i 1 here across this determines the power, that is generated in the medium and the current, which is flowing through to this can be used to vary the frequency selected.

As we know, as we discussed in the last class through Kramers-Kronig relation, Kramers-Kronig relation, the refractive index, the imaginary part of refractive index is related to the real part of the refractive index and the frequency mu q, the frequency, which is chosen by the structure lambda b here or the frequency mu q is equal to c by lambda b, the Bragg frequency here, which is equal to c divided by twice n effective, twice n effective into lambda. By changing the current here, the refractive index of this medium here changes because we are injecting carriers. The carrier injection changes the imaginary component of the refractive index and this in turn causes the change in n r, the real component of the refractive index and that causes, so here n effective, n effective is, depends on, so n effective is the effective index of the mode.

Please see, that there is a mode propagating here. The mode is propagating back and forth. n effective is the effective index of the mode, which depends on the refractive index of the active region as well as the cladding region. By changing the current i 2, we can change the refractive index of the cladding region and therefore, we can change the refractive index of n effective and thus, we can change the frequency mu q, the lasing frequency or mu q. In this case, let me call it as mu b, the Bragg frequency because we are using the Bragg structure. So, mu q is the normal notation for the resonance frequency, but in this case I will use mu b, because we are looking at the Bragg frequency. So, we can vary mu b or lambda b, we can vary the Bragg frequency for Bragg wavelength by changing n effective, which takes place due to a variation in the current and this leads to the output, which is coming from here. So, the output is here and this end is anti-reflecting coated because this part is the…

So, this has two segments. The electrodes are independent, the current i 1 and i 2 can be controlled independently. i 1 is adjusted in such a way, that this segment provides gain amplification and therefore, the power output is primarily controlled by i 1, whereas i 2 is used to control the frequency, to change the frequency. So, typical, typically one can tune the tunable range, tunable range by changing the current, is typically of the order of 5 to 10 nanometer. In the case of an external cavity laser we know, that the tuning range ECL, in case of ECL, the tuning range is of the order of 50 nanometer one can achieve in that kind of tuning range. But in general, you can vary, you can vary, the frequency of the wavelength in the range of 5 to 10 nanometers.

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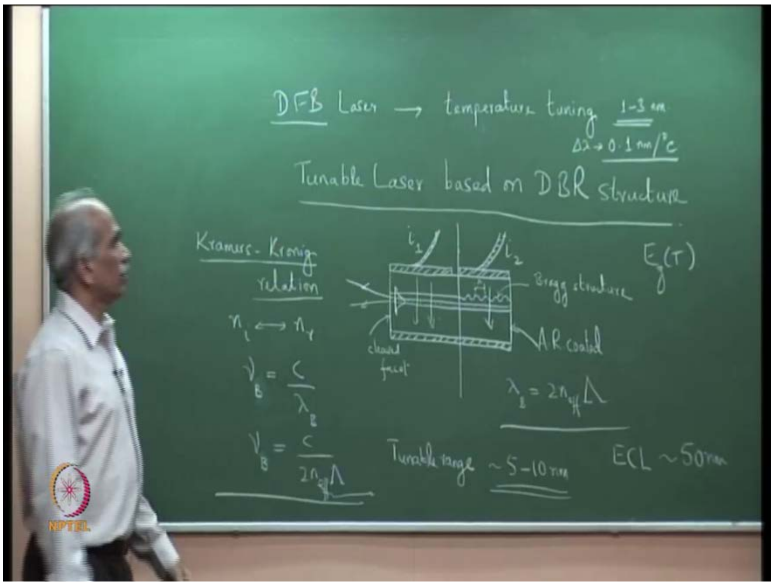

So, this is a tunable laser based on the DBR structure. We can also tune the frequency, we have seen the DFB laser, DFB laser structure in which we can tune by temperature, temperature tuning. Temperature tuning, usually a change in temperature causes the change in band gap of the active material. Almost all DFBs laser are provided with small tuning by temperature, a small range of tuning by temperature, just called temperature tuning, typically about 1 to 3 nanometer. This is the tuning range, approximately 1 to 3 nanometer. By changing the temperature, temperature tuning, typical change is about 0.1 nanometer per degree centigrade that is, delta, lambda. The change delta, lambda is typically about 0.1 nanometer per degree centigrade, so by changing the temperature one can tune the laser output. Changing the temperature, temperature tuning primary refers to tuning due to a variation in the band gap variation.

In the band gap we know, that band gap E g is a function of temperature for semiconductors; E g is a function of temperature, and therefore if you change temperature, E g changes, band gap changes and therefore, the emission wavelength also changes. So, DFB lasers are usually provided with temperature controls by changing, which we can slightly tune the wavelength, whereas this is the tunable laser based on the DFB structure. So, we will proceed, there is another scheme along with the external cavity lasers to achieve durability of laser output. Note, that the change in current here does not cause change in the power; we can maintain the power. We will continue our discussion of VCSEL, vertical cavity surface emitting lasers.