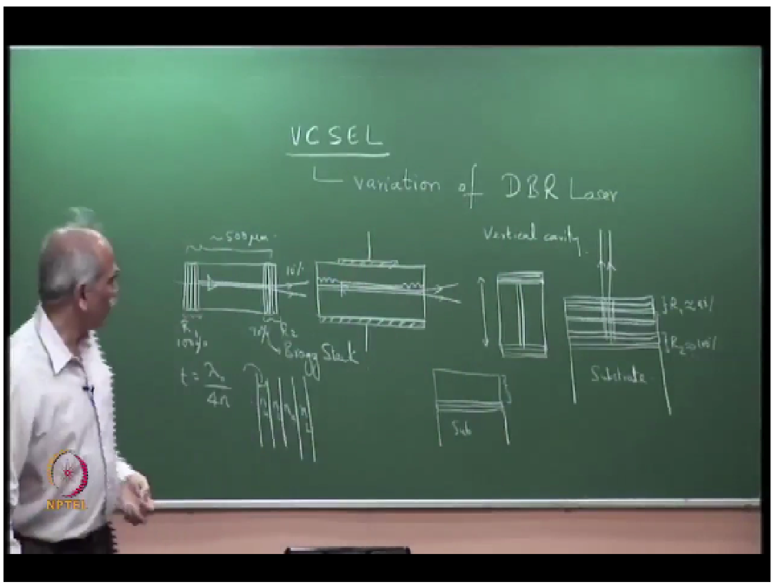
Semiconductor Optoelectronics
Prof. M. R. Shenoy
Department of Physics
Indian Institute of Technology - Delhi

Lecture – 36
Vertical cavity Surface Emitting Laser (VCSEL)

So today we will discuss about the vertical cavity surface emitting laser. This is a variation, so it is a VCSEL, vertical cavity surface emitting laser.

(Refer Slide Time: 00:26)



We can think of this as a variation of DVR laser. In the last class, we discussed about DFB and DBR laser, distributed Bragg reflector laser. So recall the DBR structure, there is the active region and there are corrugations here that is periodic structure. The frequency is selective, periodic corrugations there and this is the DBR and I had discussed that this was basically to have a cavity here, a Fabry-Perot.

How this came up that if we can put frequency selective layers here, frequency selective reflection layers, each layer is of thickness lambda/4n. So these are the Bragg stacks, that is 1 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=lambda, lambda is the wavelength you want to select.

So lambda or lambda 0/4*n, the thickness of each layer whatever wavelength thickness each one of that. 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 VCSEL, if I rotate this through 90 degrees, just rotate this through 90 degrees. So what we have is structure like this. In this case, the cavity, the 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 degrees; however, typical length here in a 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 DFB and DBR, it is 500 to 1000 micrometer, typically between 500 and 1000 micrometer because you need relatively longer lengths 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 the 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 you want to deposit, epitaxially you deposit, whatever thickness that you want and then if you like this, the thick layer here, it is normally not possible by epitaxing to grow layers thicker than 10 micron.

By epitaxy, normally you can grow layers 0.1 micrometre, 1 micrometre, 2 micrometre, 5 micrometre 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 stacks here, the Bragg stacks for reflection and then you deposit the active medium and then you have again a Bragg stack for reflection. In principle it is fine, the reflectivity, there are mirrors of reflection R1 here, R2.

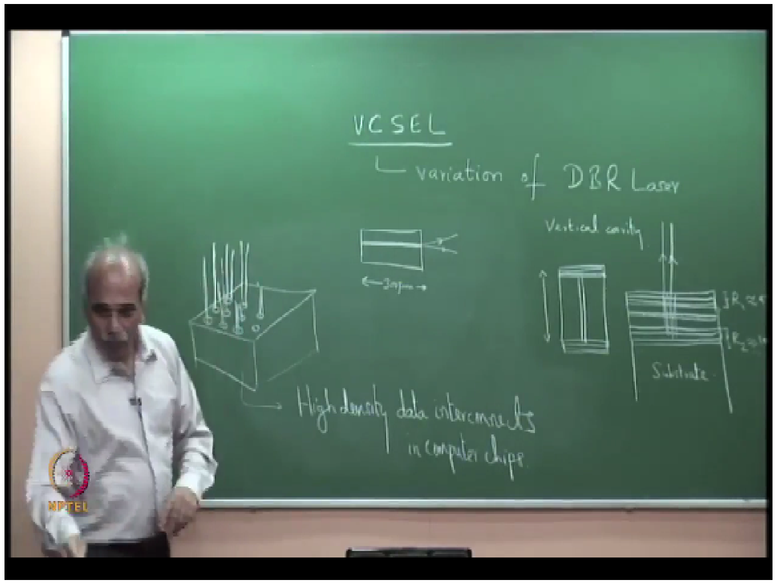
Please see this is R1 R2 which stacks provide reflectivity. So R1 R2 and this is the active medium. So you in the active medium, if you do need a double heterostructure, so there is a double heterostructure here and what results is the vertical cavity surface emitting laser? Why is it surface emitting 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, if you realize a laser substrate, then this 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, reflectively at one end if you are depositing yourself, you want this to be 100%. Let us say this is 100% and this is 95% or 90% these reflecting layers.

Please see this is no more cleaved edges, it is reflecting layers which we have deposited. So you have made reflectivity 100%, reflectivity 90% which means 10% of light is coming out of the cavity. So I have just rotated this and made this cavity here. So you have made a reflectivity nearly 100% newly and reflectivity nearly 90%, let us say. Then 10% of the light is coming out. This is the structure. So vertical cavity surface emitting laser, so it is vertical cavity on the substrate we 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 will be more clear. 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 is simply is a variation of a DBR laser where you have rotated the cavity to 90 degrees so that output is coming from the surface. Why do we want such a structure?

(Refer Slide Time: 08:31)



Because then on a chip like this, on a chip, you can grow large number of lasers all emitting to the top, upward. So this is the top view I am showing. So all of 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.

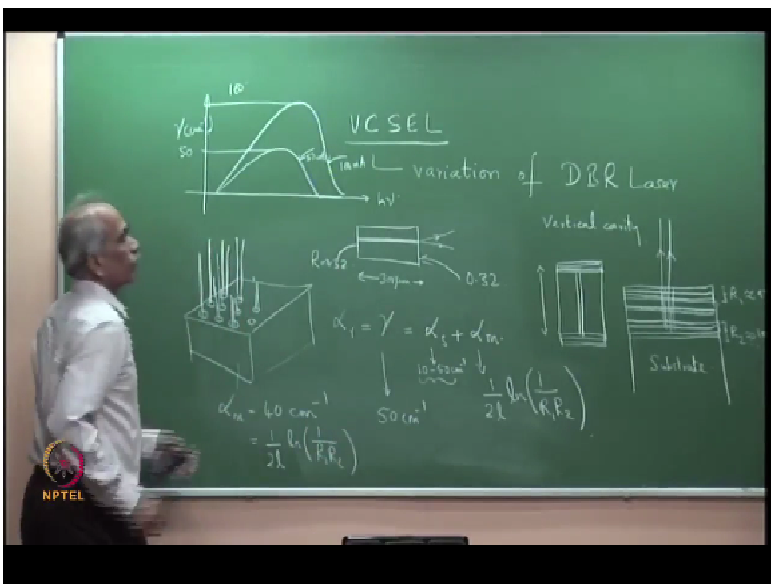
For pumping other lasers, you can make array of such lasers and today, there are lasers which can give up to 1 watt in this structure. Initially when vertical cavity lasers were made, the output was very small tens of microwatt but today, there are 100s of milliwatt from each element is possible. So 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 lasers like helium-neon laser or Nd-YAG lasers, very small, very compact, about 300 micrometer length or 500 micrometer length. This is very large compared to microelectronic components. Microelectronic components are 1 micron. So these are very large, so very bulky. It is all right 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 lasers as I mentioned one of the most important applications 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 these lasers can be modulated at tens of gigabit per second speed.

Directly you can modulate this at speeds of tens of gigabits and you can have a million component on 1 cm square. You can imagine the data density which is possible with such systems whereas these ones if you want to put a million component, it will be very bulky. For communication, it is okay because you need 1 transmitter which may have say tens of laser diodes but for high-density data interconnects, this is a primary application for which VCSELs have been developed, all right. So I come to the numbers. I come to some numbers.

(Refer Slide Time: 11:54)



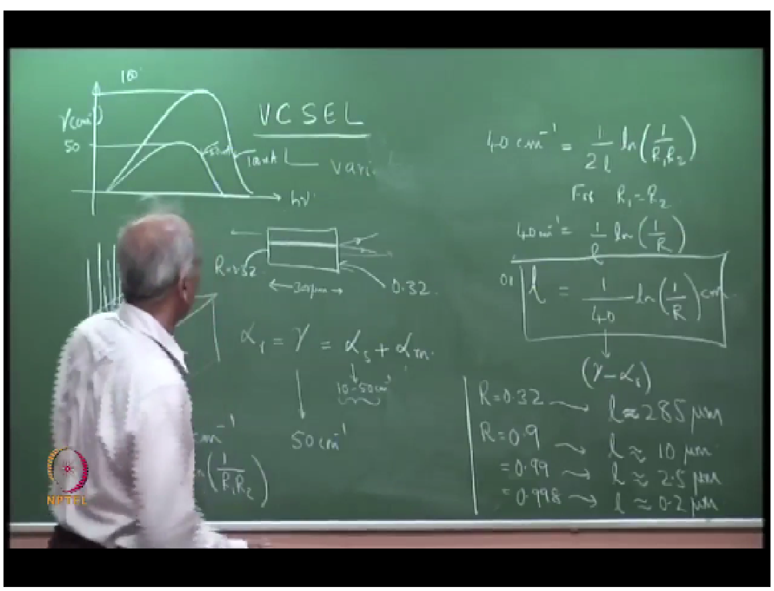
In a normal laser, this R was 0.32, cleaved ends, reflectivity of 0.32. You recall that we had an expression, the resonator loss must be equal to gain, for the laser oscillation, steady-state laser oscillation and the resonator loss is given by alpha s+ alpha m, 2 components, one mainly due to scattering and refraction losses and second is due to mirrors. So this mirror loss is 1/2l*ln1/R1R2 and typical gain profile if you see the gain profiles 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 milliampere is the current and this is for 100 milliampere, typical numbers that we have here are let us say 50 gamma centimeter inverse. So just have a (()) (13:14) 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, I am doing some example calculations, you see the importance why?

Alpha is I had mentioned that typically this is in the range 10 to 50 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 a particular example of a particular laser. You are sending a forward current of 50 milliampere and the peak gain coefficient is 50 centimeter inverse and if I assume that alpha s is 10 centimeter inverse, then alpha m should be at least 40 centimeter inverse, okay.

So alpha m=40 centimetre inverse. All these numbers are typical numbers and remember that alpha m1/2l*ln1/R1R2.

(Refer Slide Time: 14:41)



Let me continue in the calculation here. This is a very important example because what I am going to do is to give you an answer why did we take this as 300 micron. In one of the classes, I gave you an answer why the thickness of the layer was 0.1 to 0.2 micron. Now I am going to answer why this was 300 micron? You are not just taking arbitrary numbers. There are reasons for every number, all right. So alpha m here= so 40 centimetre inverse=1/2l*ln1/R1R2.

Assume that R1=R2. Assume that R1=R2. For R1=R2, what will this be? This will be whole square, so ln, so 2 2 cancels, so this will be = 1/l*ln1/R=40 centimeter inverse or l=1/40 centimeter here, 40*ln1/R centimeter. This 40, what was this 40? This was actually gamma-alpha s. If you want to write formula, it will be 1/gamma-alpha s*ln this. In my example, it was 40. Actual formula is 1/gamma-ls*ln1/R, okay.

If you substitute value, if you put R=0.32 and substitute in this, you will find that l=285 micrometers. The point is, so if you need 40 centimeter inverse as gamma-alpha s, then length has to be 285 micrometer if R is this much. If I increase R, what will happen? If I increase R, see this it is 1/R; therefore, this number will decrease and therefore l will decrease. So if I put R=0.9 that is 90% both mirrors, okay, then you will get l, please check these numbers, approximately l=10 micrometers.

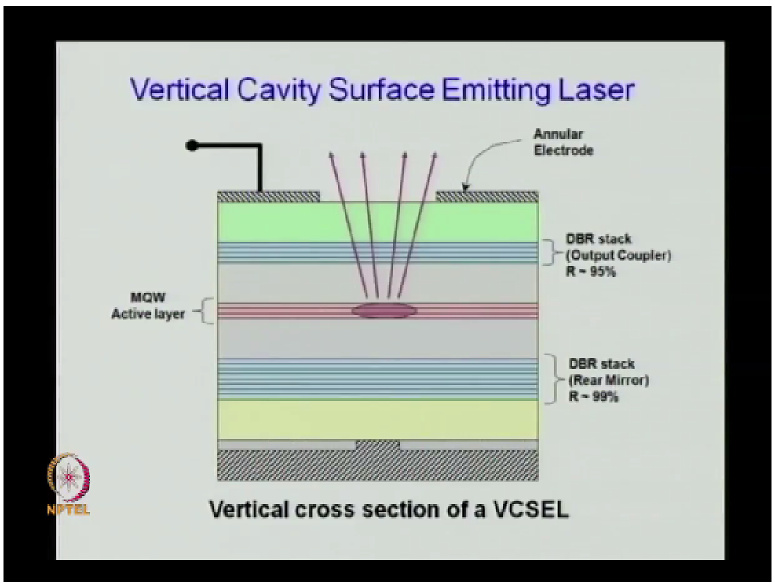
If I make R=0.99 l is nearly = 2.5 micrometer. If I make R=0.998, almost approaching 100% reflectivity, l=0.2 micrometer. What do these calculations tell? You can have thickness of the gain; l is what? length of the gain medium. If I want to reduce this length of the gain medium, the reflectivity must be high; otherwise, alpha will blow up, alpha has l in the denominator. So if l reduce, alpha will increase unless I also increase this.

If R comes close to 1, note that if R=1 ln is 0. So if R comes close to 1, then you can reduce the R; otherwise, you cannot reduce l. So in a normal laser because this was 0.32, you require at least 300 micron that is that much length of the gain medium to make up for the losses from the resonator. If reflectivity is 32%, it means 68% 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 mention, 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 laser, 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, through this example, we have answered this as to why it was 300 because it was simply cleaved ends, you could not have gone less than that and how to go to small thicknesses? By increasing high reflectance and therefore you see now the structure of the vertical cavity surface emitting laser. We will see the structure here.

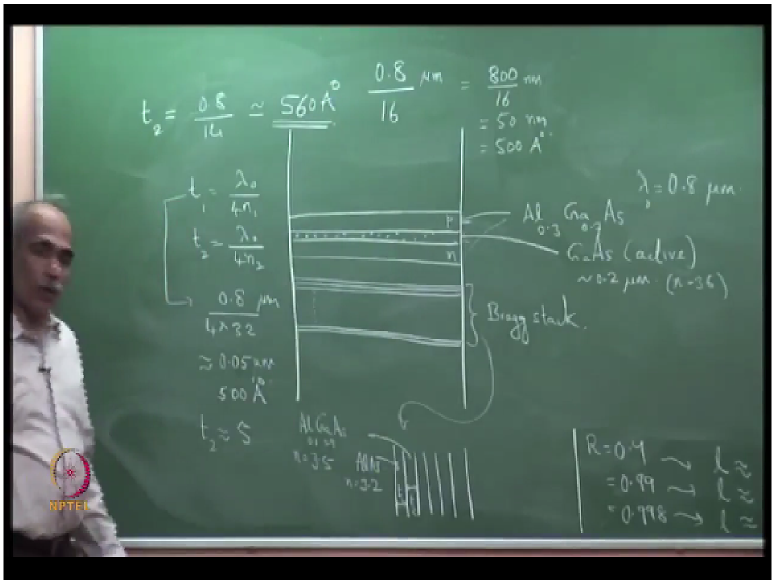
(Refer Slide Time: 20:45)



So here is the vertical cavity surface emitting laser. Please project this. So there you go. You can see the structure very clearly. The structure comprises of, if you see, this is the substrate here and you have a Bragg stack here which provides reflectivity, high reflectivity and then here is the active layer. This active layer is basically a double heterostructure. 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 well structures.

In double heterostructure, the active layer is these days' multiple quantum well structures. What is this multiple quantum well structure? We will see in the next class but this is our active region and outside these 2 are cladding regions. This is the active region which forms the double heterostructure and here is the reflectivity provided by the upper mirror. So that is a 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 a basic structure.

(Refer Slide Time: 22:25)



So let me draw it here. You have, because there is one more layer in between which is mixing. So I will show that. So you have the active layer here which we normally show by dotted line. Outside this is the cladding region. So this is the one which forms the double heterostructure. A low band gap materials sandwiched between higher band gap material, all right. In simple terms, this could for example, this is a gallium-arsenide laser, then this is gallium arsenide active layer.

So active, so typically the thickness is 0.2 micrometre. Outside is the cladding layer. If this is gallium-arsenide, let me say that this aluminium-gallium-arsenide Al 0.3 gallium 0.7 and arsenic. So both are aluminium-gallium-arsenide here. So this is p, this is n, this is p and below this, we have the lower Bragg stack. So here the Bragg stack. So number of layers are there. Typically, people use about 25 periods here.

So this is the DBR Bragg stack. For example, this Bragg stack may comprise of, so let me show here, the Bragg stack will comprise of high low high low layers. So this is for example this piece aluminium arsenide, this refractive index is 3.2. lower refractive index and this one is gallium-aluminium. So aluminium 0.1, gallium arsenide, so gallium 0.9 aluminium 0.1, gallium 0.9, arsenide.

Remember that gallium arsenide has a refractive index n nearly = 3.6 and aluminium arsenide has a large band gap, refractive index is 3.2. This is approximately n=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 t1 and this thickness as t2 here, then t1=lambda 0.

Let us say the laser is gallium arsenide laser. Laser is lasing at lambda 0=0.8 micrometer say for example, the laser wavelength is 0.8 micrometer, then I have to chose the thicknesses such that lambda 0/4*n1 t2=lambda 0/4*n2 and putting some numbers so that you get a feel for the thickness of the layers. So what is lambda 0 here. So lambda 0 is so 0.8, so t1=0.8 micrometer/4*n1, n1 is 3.2, so 3.2.

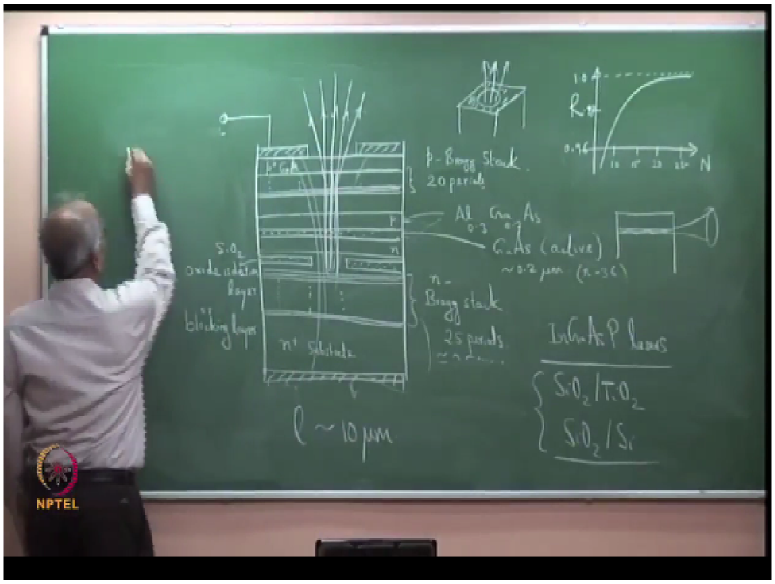
So this is 4*1/16. So this is nearly = 1/16 is approximately = 0.06, 0.06 micrometer, that is approximately 600 angstroms. The thickness of this layer, t1. Similarly, you calculate t2 substitute 3.5 here and you will get t2 nearly = 500, okay, let me just see. This is 4*3.5, 14, so 0.8/14, sorry.

"Professor - student conversation starts" (()) (26:59) one second, this is nanometer or micrometer, 0.06*10 power, so this is, wait, wait, wait, wait. Not nanometer, right. It is not nanometer. Just a minute. 0.8/16, so this is micrometer which is = 800, so multiply 800/16 nanometer, so this is = 600, so 60, 60 something nanometer that is 600 angstrom. I should have written 16, so exactly 500 right.

So this is nanometer, so 50 nanometer, so this is = 500 angstrom. So it is not, in this case, this is exact, I am sorry. So please correct this. So 0.95 micrometer which is 500 angstrom. Anyhow the order was right but it is good you interrupted that I have got the correct R value now, that is now 500 angstrom, all right. **"Professor - student conversation ends"**

Similarly, please calculate for the other one. I have used the right value. So this is t1 and t2 calculate this t2. So t2=0.8/14, so this will be approximately 500 is 70 and again 10, 560, 560 angstrom.

(Refer Slide Time: 29:04)

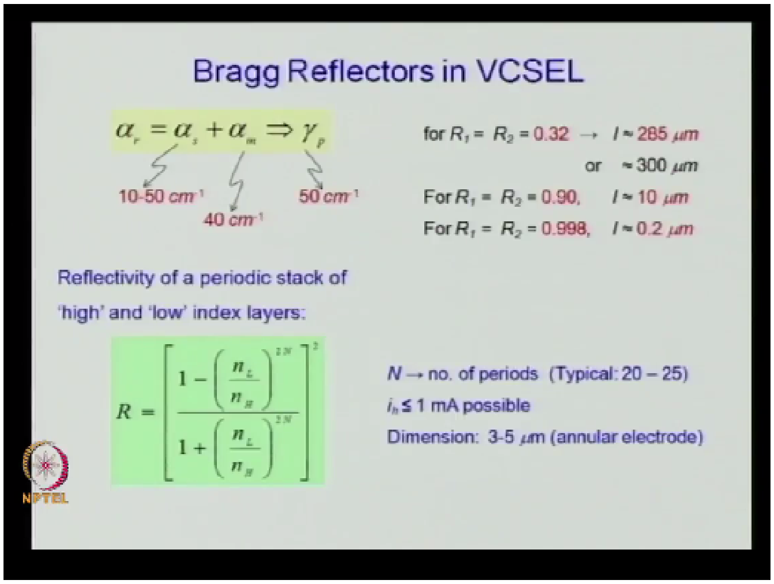


Now why did I write this? So one is approximately 500 angstrom and another is 560 angstrom. So if you add lambda, the period, please see the period here, this is lambda period is = t1+t2 with is = t1+t2=560+500=1060 angstrom. So 1060 angstroms is 106 nanometer or equal to nearly equal 0.1 micrometer, is the period. So typically people use here 25 periods and for the upper Bragg stack here, I also have an upper Bragg stack which is there in the diagram, okay.

So this is the upper Bragg stack, 20 periods. So DBR, upper Bragg stack approximately 20 periods, 20 periods mean this will come out to be about nearly = 2 micrometer thickness. See why I have put all these numbers is you get an idea what kind of thickness; otherwise, if you just write a 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 a Bragg stack 2.5 micrometer, 25 periods, larger the number of period, larger will be the reflectivity. Please see this, the reflectivity of the stack is given by the next slide there shows you the reflectivity, all right. What will I erase? So if you plot this reflectivity, I am plotting reflectivity, reflectivity is given by the formula there.

(Refer Slide Time: 31:43)



1-n low/n high to the power 2n/1+n low/n high to the power 2n whole square. So that is the reflectivity of a Bragg stack, a periodic structure where N is the period, capital N is the period. So if I plot N here versus reflectivity, typically the reflectivity varies like this. This is 1, 1.0 and here, this is approximately 0.96. This is 10 20 25 15. So what I have plotted, please see is, see this graph clearly.

Reflectivity versus, so this is 0.96, this is 0.98, so 0.98, 0.98. So by taking 20 to 25 periods, the reflectivity is approaching 0.995 996 998. So that is why you take 25 periods here so that this reflectivity is approaching almost 100% and this is almost 99.5%. So the structure, now I hope the structure is getting clear. So let us go back and see the structure there in colour. This is the active region, cladding region, the Bragg stacks.

These are the Bragg stacks. So I have written 25 Bragg stacks here, 25 periods here. It is called the Bragg stack. This is a stack of layers and above these, you have the annular electrode and the window. Window for the laser light to come out. This is the metallic electrode, the contact positive. So this is p+ 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+ and this is n + substrate.

So this is longitudinal cross-section. What is shown on the screen is vertical cross-section of the laser. So 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 (()) (35:11) on top of the substrate. So substrate is below, 50 to 60 micron and this is annular electrode.

So please remember that if you see the 3D view, then it would have an annular electrode. Unfortunately, I did not have a diagram which showed a 3D view. So here is the… So the light is lasing here in between, it is building up here, so the light is building up here and coming out of the surface. This 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 careers would go here. So if this is blocked, this is SiO2, usually SiO2 this is, oxide layer, blocking layer. Then the carriers would go like this. So that light is generated here because you want light to come out here. If this is not there, then carriers will flow here. So that is why this layer is used, isolation, oxide isolation layer or blocking layer so that the light is generated in the central portion and this is the top view.

So light comes from here. So usually the electrode is annular and the output that you get is circular. One of the important advantages of VCSEL over the Fabry-Perot lasers, we have the output characteristics of Fabry-Perot lasers. 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.

Whereas in this case, it is a circular cross-section beam. It is confined identical because you see they are all layers. So it is plane where it is going up and down. It is only layer, there is no wave guidance. There is no optical wave guidance here because 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, it diffracts.

Here the light is going just up and down. There is no optical wave guidance and therefore the beam output is circular in process. It is also an advantage. If you want to couple these 2 optical fibres, the coupling efficiency of this will be much more compared to the coupling efficiency here, because fibres have a circular cross-section and therefore if the beam is elliptical in cross-section, the coupling efficiency will be poor.

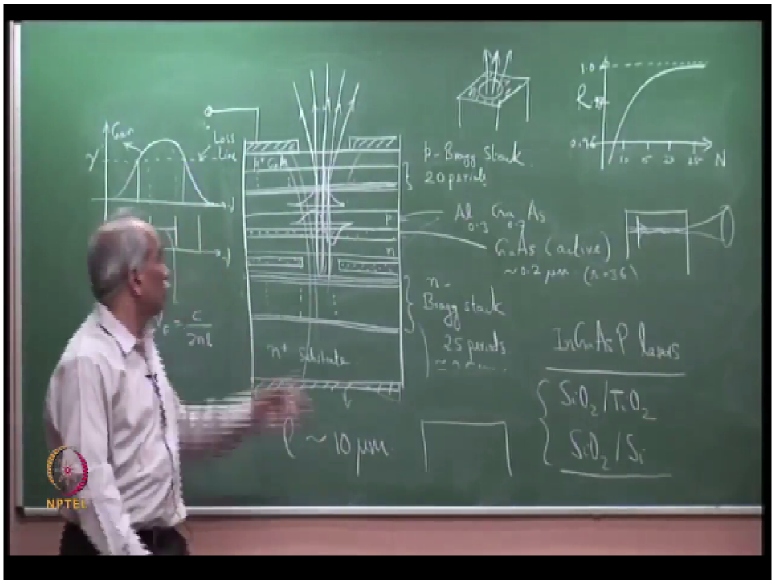
So I have taken the example of gallium-arsenide laser here and therefore the Bragg stacks are normally used made up of aluminium-arsenide and aluminium-gallium-arsenide but in the case of Indian gallium arsenide phosphide lasers, usually the Bragg stack comprises of SiO_2/TiO_2 or SiO_2/Si layers, alternate layers of SiO_2/TiO_2 and SiO_2/Si layers. TiO_2 is conducting as you know titanium oxide, tin oxide or 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, there was no problem, it was semiconductor and this is N-doped. All layers are N-doped, all layers are P-doped. So it is still a PN 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 centre and current flows from the side.

There are special structures, if you can see in the literature that the layers do not run from end to end here. The Bragg stack is only in the central region and the sides comprises of semiconductors. So most of the SiO_2/TiO_2 Bragg stacks are realised only in the central portion. There are very special structures where you etch and deposit only in the central region because in this region, light is building up.

One last point is that the length of the cavity here, so this length we have seen that it is approximately, total length is less than or of the order of 10 micrometer. Please recall that this is 2.5 micrometer, this is 2 micrometer and this is about 1 or 2 micrometre which means the total cavity length is less than or of the order of 10 micrometer. If the length is very small, the free spectral range is very large.

(Refer Slide Time: 41:23)



Recall that the 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 both the cases, the axis is new. So this axis is frequency nu, this is gain gamma, and this is resonance frequencies nu and this is the free spectral range nu F=C/2n*l. Unlike the case of bulk semiconductor lasers, here l is very small, l is of the order of 10 micrometer which means nu 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 application bandwidth because this is the loss line. Recall the last class, loss line and this is the gain curve, so gain. So within the amplification bandwidth that is net amplification where the gain is more than loss, you normally have 1 mode, I have shown. In this case, there are 2, there appears to be 2 but normally the separation is large enough so that there is only one longitudinal mode.

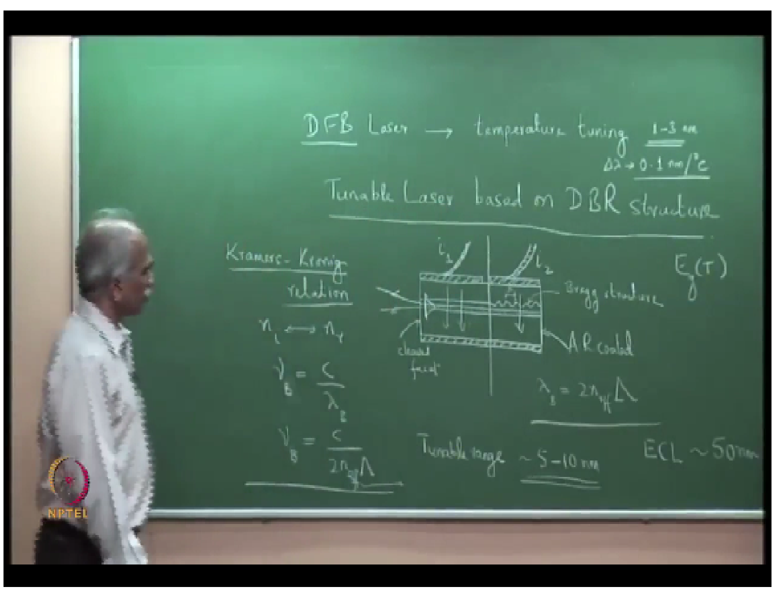
And therefore, usually VCSELs are single longitudinal mode structures. So this also falls in the class of single frequency measures, just like DFB and DBR lasers, VCSELs are also single frequency lasers because the frequency is selected here also by the Bragg structure and the cavity is also very small 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 structure currently. There are several problems with VCSELs, several issues that when you have to grow a large number of VCSELs on a substrate, writing this annular electrode a 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 control, control of the transverse field.

In this case, the transverse mode is determined by the optical wave guide. So there is no problem. You know exactly what is the mode shape. What is the transverse field? In this case, there is no guided mode because it is 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 mode, this is an issue and there are large efforts to control this mode profiles of the transverse mode profile.

More recently people are using photonic crystal structures. The upper Bragg stack comprises of photonic crystal structures for controlling the mode shape. So a considerable advance is still going on in the case of VCSELs. So we will stop here for the VCSEL and in the next class, we will discuss about quantum well lasers.

(Refer Slide Time: 45:25)



Before I proceed with the discussion on VCSEL, let me discuss a small topic that is a tunable laser based on DBR structures. In the last class, we had discussed about DFB lasers and DBR lasers and also we have discussed about tunable lasers based on external cavity and rotating grating. So both are forms of tunable lasers. At another structure which is used as 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 2 segments, this is the active region, the actively layer one segment, the structure has 2 segments basically. In terms of electrodes, there are 2 electrodes. In the cladding, the DBR grating is at one end. The DBR grating is only at one end. So this is the cleaved facet. This end is antireflection coated, AR coated and this is the Bragg structure which determines the frequency.

So depending on the period lambda, so this is lambda, the period is lambda. So depending on lambda, we have the wavelength, the wavelengths lambda b selected will be given by 2n effective*lambda. So the frequency is selective. Bragg structure is at one end of the device and this has 2 electrodes here. I am showing, these are the contact electrodes. Current I1, so I1 is the current to this and I2 is the current to the 2 independent electrodes.

The current I1 and I2 can be controlled separately. This is the active region and the current which is flowing I1 here across this, determines the power that is generated in the medium and the current which is flowing through this, can be used to vary the frequency selected. As we discussed in the last class, through Kramer-Kronig relation, the refractive index, the imaginary part of the refractive index is related to the real part of the refractive index and the frequency nu q, the frequency which is chosen by the structure, lambda b here or the frequency nu q=C/lambda b the Bragg frequency here which is=C/2n effective*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 a change in nr, the real component of the refractive index and that causes, so here it is n effective, n effective is the effective index of the mode. Please see that there is a mode which is 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 regions. By changing the current I2, 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 nu q, the lasing frequency or nu q.

In this case, let me call it as nu b, the Bragg frequency because we are using the Bragg structure. So nu q is the normal notation for the resonance frequency but in this case, I will use nu b because we are looking at the Bragg frequency. So we can vary nu b or lambda b. We can vary the Bragg frequency or Bragg wavelength by changing n effective which takes place due to a variation in the current and this leads to output which is coming from here, so the output is here and this end is antireflection coated.

So this has 2 segments, the electrodes are independent, the current I1 and I2 can be controlled independently. I1 is adjusted in such a way that this segment provides gain amplification and therefore the power output is primarily controlled by I1 whereas I2 is used to control the frequency, to change the frequency. So typically one can tune the tunable range by changing the current, is typically of the order of 5 to 10 nanometers.

In the case of an external cavity laser, we know that the tuning range, ECL the tuning range is of the order of 50 nanometers. We cannot achieve that kind of tuning range but in general, you can vary the frequency or the wavelength in the range of 5 to 10 nanometers. 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.

Usually a change in temperature causes a change in band gap of the active material, almost all DFB lasers are provided with a small tuning by temperature, the small range of tuning by temperature which is called temperature tuning, typically about 1 to 3 nanometers. This is the tuning range, approximately 1 to 3 nanometers by changing the template. 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 the band gap Eg is a function of temperature for semiconductors. Eg is a function of temperatures and therefore if you change the temperature, Eg changes, band gap changes and therefore the emission wavelength also changes.

So DFB lasers are usually provided with temperature controls by changing which you can slightly tune the wavelength. Whereas this is a tunable laser based on the DFB structure. So we will proceed. So this is another scheme along with the external cavity lasers to achieve durability of the 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 VCSELs, vertical cavity surface emitting lasers.