Integrated Photonic Devices and Circuits
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Lecture - 38
Light Sources and Photodetectors for Integrated Photonics: Integrated Photonic Light Sources

Hello everyone, today we are going to start the start a new chapter and the last chapter of course for this course, light sources and photodetectors for integrated photonics. First we will be discussing about integrated photonic light sources you will know there are various type of light sources available, but we will be discussing something suitable technologically suitable for integrated photonics or photonic integrated circuits.

As you as we say integrated photonic, photonics or photonic integrated circuits. So, waveguide is the fundamental building block. So, I think we have to concentrate more on light sources or laser source which is designed based on waveguide. So, I will be discussing about waveguide laser fundamentals and then as you know semiconductor laser diode that means a light emitting diode or laser diode.

These are actually the most efficient light sources and how those types of semiconductor laser diodes can be integrated that is the challenge for the photonic integrated circuit of course, that will be discussed in this course. But, before going into that, in detail, we will be just discussing about the working principle of semiconductor laser diodes, so, let us move on to the waveguide laser fundamentals.

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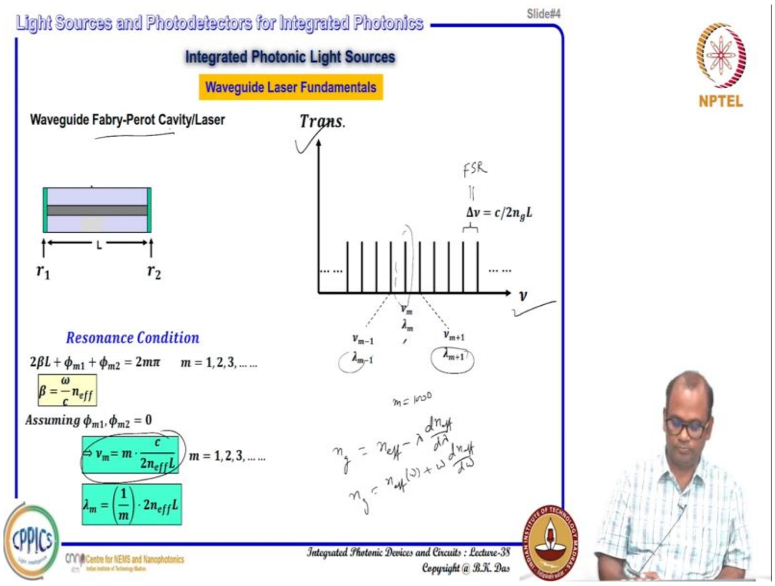

Light Sources and Photodetectors for Integrated Photonics

Slide#4

Integrated Photonic Light Sources

Waveguide Laser Fundamentals

Waveguide Fabry-Perot Cavity/Laser

Resonance Condition

$2\beta L + \phi_{m1} + \phi_{m2} = 2m\pi \quad m = 1, 2, 3, \ldots\ldots$

$\beta = \frac{\omega}{c} n_{eff}$

Assuming $\phi_{m1}, \phi_{m2} = 0$

$\Rightarrow \nu_m = m \cdot \frac{c}{2n_{eff}L} \quad m = 1, 2, 3, \ldots\ldots$

$\lambda_m = \left(\frac{1}{m}\right) \cdot 2n_{eff}L$

$m = 1000$

$n_g = n_{eff} - \lambda \frac{dn_{eff}}{d\lambda}$

$n_g = n_{eff}(\omega) + \omega \frac{dn_{eff}}{d\omega}$

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So, it is not much different from laser fundamentals, the laser working principle, just we will be using instead of a pre running electromagnetic wave or light source light energy, we will be considering that guided mode, that is it. So, we start with a waveguide Fabry-Perot cavity as it is shown here, a waveguide here, this is the top view of the waveguide it can be a single mode.

That means, the confined like this the field distribution will be like this laterally it will be confined and vertically it will be confined, but it will be allowed to propagate in one direction, but with a certain length you can have some kind of mirror here. So, these mirror here and these 2 mirrors so, that means the waveguide both in facets you can deposit a mirror and or you can think of that the waveguide instead of this mirror.

This mirror can be a DBR mirror. So, it can be DBR 2 Distributed Bragg reflector 2 and this can be also this side you can extend that you can have a mirror DBR mirror DBR 2, DBR 1. So, instead of just standard dielectric mirror deposition, you can think of distributed Bragg reflector integrated into the waveguide that will give you selective reflectivity for certain bandwidth.

So, that can also be considered we have discussed earlier already DBR cavity. So, you can think of that type of cavity as well, but for understanding purpose we just consider a long mirror here and giving you reflectivity r 1 small r 1 small r 2 the small r 1 we mean that means the reflection coefficient amplitude reflection coefficient normally intensity deflection coefficient I can write like this r 1 r 1 star and r 2 this one r 2 star.

That would be your normally called reflectivity of mirror 1 and mirror 2, but r 1 r 2 that could be is simply amplitude flux and coefficient of the guided mode and then we know that this Fabry-Perot cavity standard resonance condition we discussed earlier also just reproduced here that phase because of the phase acquired because of the round trip travel. So, one round trip, if beta is the propagation constant defined by beta = omega / c n effective n effective is the effective index of the guided mode.

Can we also did in terms of lambda 2 pi / lambda n effective this n effective can be also lambda dependent or frequency dependent and then this is the phase constant for a given lambda and then round trip total phase and this pi m 1 and pi m 2 if at all any phase being introduced by mirror 1 and mirror 2 respectively. So, for a one round trip it goes here travels here beta m phase comes back with a reflection and phase pi m 1.

Again beta l phase and again gives you pi m 2 then one round trip completes that means, one round m means double pass and then double reflection from mirror 2 and mirror 1 respectively. So, this would be pi m 1 this would be pi m 2. So, if this rounded phase is equal to 2 pi times integer m = 1, 2, 3 and so, on then we can say that, that particular omega or that lambda is resonant to the cavity.

So, electromagnetic wave or guided mode associated with that lambda that will see some kind of energy storage it will be seeing some resonances. So, that thing for that discussion to proceed what we consider here just for simplification pi m 1 and pi m 2 most of the time if it is dielectric material they can be 0 they can be assumed to be 0, but if it is a DBR for example, you can have this pi m 1 and pi m 2 both if it is DBR 2.

For example instead of this mirror replaced by DBR 2 and this mirror replaced by DBR 1 as you know reflectivity parameter distributed Bragg reflection reflector integrated with a waveguide that can be frequency dependent as well as that can be every frequency that can have different phases also. So, that need to be considered for the moment we are discussing their 0.

So, in that case, I can just consider beta = omega / c and then always omega we can write like 2 pi 2 pi / nu omega is the angular frequency and nu is the linear frequency. So, in terms of resonance frequencies, we can express that nu m = m c over to any effective L, L is the total length of the cavity. So, now, again we know that nu lambda = c velocity of light they are related.

So, we can just convert nu into lambda then we can find this one m is the integer. So, depending on the length you can find out to have for example, if you want to have a resonance wavelength around 1550 nanometre and for a given length say 1 millimetre and n effective for silicon waveguide for example, if I just consider that is around 2.8 or so, then you can find what is the value of m required.

So, that is the integer value that would be considered as an order of the longitudinal mode m is the actually counting the order of the longitudinal mode m = 1 that first order longitudinal mode m = 2 second order longitudinal mode because we are considering resonance in the round trip path. So, it is called longitudinal modes and those longitudinal modes actually if you want to represent or if you want to see as a function of frequency here X axis is the frequency and Y axis is your transmission.

Transmission if you see then we can say that a certain range of frequencies you put consider this equation n effective and L if you are considering suppose constant for example, if not does not depends on effective index depends on frequency for example, if you consider. So, in that case that regularly you will be getting this one for example, assigned as a nu m or lambda m, m can be say 1000 depending on your wavelength.

Your effective index and length and then you can have nu m - 1 Whenever m = m - 1 then can have another frequency because we can see will be reduced m + 1 frequency will be increased corresponding lambda m + 1 lambda m - 1 you can find like that and we have also shown that such longitudinal resonance frequencies, they are spaced by a term called pre spectral range FSR and FSR is equal to delta nu you are represented.

That means, the separation between successive resonance frequencies and they can be expressed by c over to n g L where n g L is the group index we have shown earlier that that is nothing but if it is in terms of lambda n effective is given, then you can write like this otherwise, if n g n effective is given in terms of frequency then you can write omega d n effective / d omega.

So, this is the group index. So, depending on the group index that means, how much is the dispersion in the waveguide involved that actually decides the separation between longitudinal frequencies. So, this is all what we have discussed about Fabry-Perot cavity and that has been discussed earlier of course, in this course, but here we have just repeated the same discussion just to understand how a Fabry-Perot laser works.

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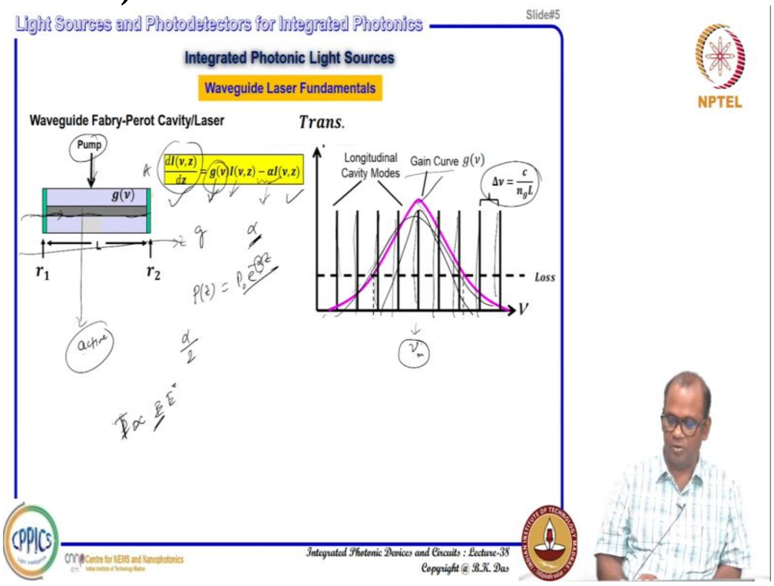

Light Sources and Photodetectors for Integrated Photonics

Slide#5

Integrated Photonic Light Sources

Waveguide Laser Fundamentals

Waveguide Fabry-Perot Cavity/Laser

$$\frac{dI(\nu,z)}{dz} = g(\nu)I(\nu,z) - \alpha I(\nu,z)$$

$$\Delta\nu = \frac{c}{n_g L}$$

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Now, let us see, suppose in this waveguide you have somehow some energy supplies there you have certain kind of pump then such that in this waveguide it becomes active when active means any signal electromagnetic wave signal with a certain frequency that can get some kind of that can see some kind of gain amplification. So, if that pump is given some energy is given such that your signal propagating through this electromagnetic signal propagating through the waveguide will see some kind of gain.

If that gain coefficient is given by g and that can be frequency dependent and i is the intensity that is also frequency dependent and position dependent that as it propagates it will see some kind of gain it will be increasing. So, we can write down that equation the evolution of intensity or power i can be written as a power also. So, a cross section of the waveguide is multiply you just multiply cross section of the waveguide left hand side and right hand side that will give you some power evolution equation for power revolution.

So, you can see that this rate of change of our differential change of intensity shown by here that must be proportional to the intensity and gain coefficient and of course, you should count also the loss, loss parameter of the waveguide remember that this g and alpha this is actually the loss parameter of the power loss power loss coefficient. Suppose, if you have power at z if you want to define from p 0 e to the power - alpha z.

So, that this is actually power loss coefficient earlier you remember that alpha we normally consider alpha as the loss coefficient for the amplitude. So, if alpha is the loss coefficient for the power so, amplitude loss coefficient will be alpha / 2 because you know power is nothing but power or intensity is nothing but E is E star. So, if electric field loss coefficient if you are considering that is alpha / 2.

Then E E star becomes alpha. So, intensity loss coefficient can be alpha. So, if it is that so, we can write down the intensity evolution along the waveguide suppose, we are considering this is z direction we can write like this and this gain curve as I mean some depending on the pump depending on the material you are using that is actually how is this active waveguide you are defining what type of material all these types of things actually involves mostly in physics.

If you see that actually involves what is the energy band diagram of the material used for the waveguide under consideration and also how is the population inversion is created population inversion is very well known very much known in laser physics, I will be discussing in terms of semiconductor here. So, that that can have frequency dependent this g can be frequency dependent.

But alpha we are considering that it may be flat for all frequencies under consideration. So, here it is shown that gain curve these are the longitudinal frequencies of the cavity we have shown earlier the previous slide these are the longitude and frequency and their separation delta nu = c / n g L as we have given and you say this is the gain curve. So, that means, suppose this is your nu m for a here we are shown.

So we are considering that this gain is some material is such that it is actually giving maximum gain around the m th resonance frequency and it may be wavy type or any type of it can be different type of set it can be something like this type of shape also. So, it will have it will have some kind of bandwidth and it will have some kind of distribution gain distribution frequency dependent gain distribution.

Here this pink colour is shown as a gain curve as a representative will typically it will be maximum somewhere and both side at lower frequency and higher frequencies right it will be dropping that is the typical gain curve, but the nature can be Gaussian that can be some estimated Gaussian that can be something completely different function may not be possible to represent with a function or so.

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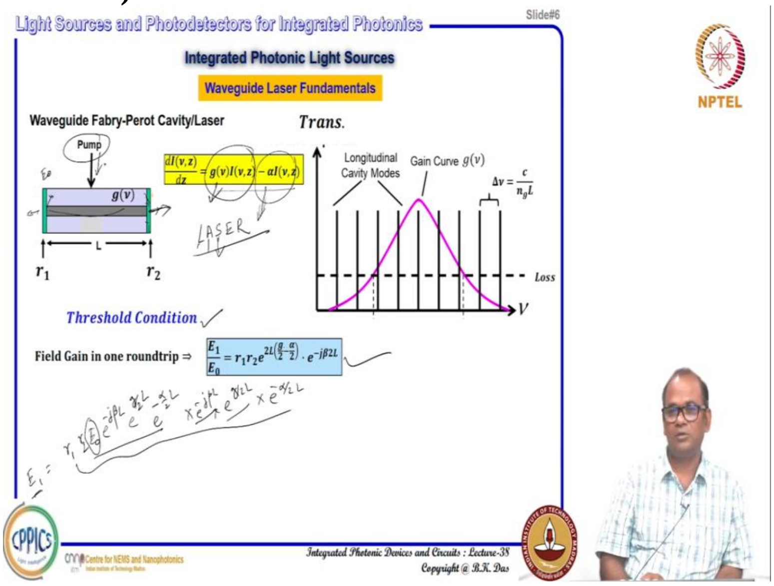

Light Sources and Photodetectors for Integrated Photonics

Slide#6

Integrated Photonic Light Sources

Waveguide Laser Fundamentals

Waveguide Fabry-Perot Cavity/Laser

$$\frac{dI(\nu,z)}{dz} = g(\nu)I(\nu,z) - \alpha I(\nu,z)$$

LASER

Threshold Condition

Field Gain in one roundtrip ⇒ $\frac{E_1}{E_0} = r_1 r_2 e^{2L\left(\frac{g}{2}-\frac{\alpha}{2}\right)} \cdot e^{-j\beta 2L}$

$E_1 = r_1 r_2 E_0 e^{-j\beta L} e^{\frac{\gamma}{2}L} e^{-\frac{\alpha}{2}L} \times e^{-j\beta L} e^{\gamma/2 L} \times e^{-\alpha/2 L}$

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Now, let us define a certain thing called threshold condition. So, normally if you know we want to discuss about laser waveguide laser, laser you know that is actually light amplification by stimulated emission of radiation, laser. So, that means light will be amplified because of the pump because of the gain and that gain actually comes with a particular term called stimulated emission.

So, emission will happen that will be stimulated that will be triggered that will be that will be initiated by some means, that is called for example, if you have a certain photon certain photon with certain frequencies propagating and if it is the medium is such that this one photon actually help to emit another photon also from the material we have same property of the initial photon whatever the property associated for the initial photon.

Then it will be called stimulated that is actually quantum mechanical process or maybe classical you can explain using a dipole oscillation etcetera we are not going into that detail, but stimulated emission required. So, that stimulated emission actually gives you gain, but that gain as you see that in this equation right hand side you have one positive term another negative term.

So, that means, you can imagine that to get a net gain you need to have g certain value of g overcoming the losses this loss in this case here we are considering that the propagation of the electromagnetic wave in a gain medium, but whenever you have a mirror that means, after travelling a L length it gives some kind of reflection into the cavity that means giving some kind of positive feedback.

And coming back again this mirror also gives some kind of positive feedback that means the when it is propagating getting gain everything fine then when reaching to the mirror then entirely will not be reflected part of that reflected some of them will be lost this side. So, here also some of them every round trip it will be lost this side a little bit this side a little bit you can imagine like that.

But thing is that pump is continuously supplying energy. So, every time it goes it amplifies a little bit loose and a little bit coming back and comes back again, so, this every round trip it goes and goes on and on. So, it will go for amplification, amplification, amplification and so on at every round trip you will get some kind of losses also, but there should be some kind of steady state condition for a given pump here.

For example supply this can be bias or whatever, so, but we would like to know that when this laser to emit is there any threshold value for the pump or not or for the gain is whether you need a certain threshold gain to have a laser emission or not significant amount of laser light emission will be there with a good property so called coherent property etcetera, for that purpose whether you need a threshold gain or not that thing we will be trying to understand now.

If there is existing at all or not or just keep on pumping, you will keep on getting some laser source or not. So, let us see now, you see field gain in one round-trip suppose, you have your initial your field what you are considering at any instant of time the E naught is the field now, after one pass this field when it goes to it is travel L length, this field will be evolved, with a pairs of this one and with a gain of field gain is g / 2 times L and it will evolve with a loss of - alpha / 2 L.

So, after one pass it gets like this and then after reaching here it sees some kind of reflection coefficient r 2 then what happens it comes back again it travels and then comes back another L length then this again it will be multiplied by e to the power – j beta L and again it will get some additional gain this is phase gain this is just amplitude gain normally and then again you will be getting some kind of loss one pass.

After coming back here again it will see reflection so, that means this we call it as a E 1. So, we started with the E naught one round trip it gives you E 1. So, if I just take E 1 / E naught that is what this comes like this, this expression you just simplify this thing, then you will be getting this thing remember that g and alpha is consider gain coefficient and loss coefficient for the intensity of the intensity travelled through the waveguide.

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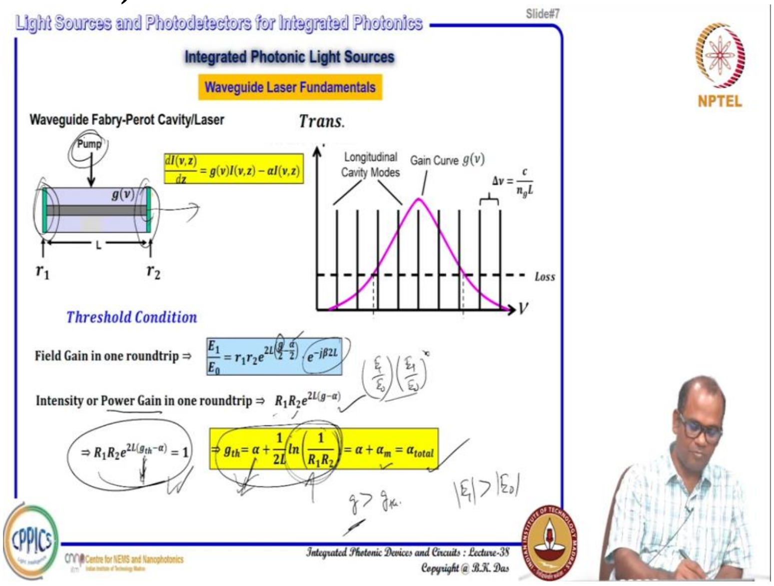

Light Sources and Photodetectors for Integrated Photonics

Slide#7

Integrated Photonic Light Sources

Waveguide Laser Fundamentals

Waveguide Fabry-Perot Cavity/Laser

$$\frac{dI(\nu,z)}{dz} = g(\nu)I(\nu,z) - \alpha I(\nu,z)$$

Threshold Condition

Field Gain in one roundtrip ⇒ $\frac{E_1}{E_0} = r_1 r_2 e^{2L\left(\frac{g}{2}-\frac{\alpha}{2}\right)} e^{-j\beta 2L}$

Intensity or Power Gain in one roundtrip ⇒ $R_1 R_2 e^{2L(g-\alpha)}$

$\Rightarrow R_1 R_2 e^{2L(g_{th}-\alpha)} = 1$

$\Rightarrow g_{th} = \alpha + \frac{1}{2L} \ln\left(\frac{1}{R_1 R_2}\right) = \alpha + \alpha_m = \alpha_{total}$

$\left(\frac{E_1}{E_0}\right)\left(\frac{E_1}{E_0}\right)^*$

$g > g_{th}$

$|E_1| > |E_0|$

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Now, what you see intensity or power gain in one round trip so, that means intensity of power gain when I am talking about gain that means E naught / E 1 that is amplitude gain and intensity gain will be E 1 E naught star that will be intensity or power gain proportional to that one then what you will see, you see complex conjugate and multiply so, this thing can be phase part can be e to the power j beta delta L.

That will be cancelled r 1 star will become r 1 r 2 r 2 star will become r 2 and this will be multiplied by 2 times complex conjugate. So, 2 will go 2 L g - alpha. So, this will be the intensity or power gain in one round trip. Now, suppose this gain is 1 that means, after one round trip you are actually reproducing that energy whatever energy is being lost or gain after one round trip it is just 1.

So, that means, you have nothing lost you are losing nothing or you are gaining nothing. So, that type of situation that type of gain when you are that type of condition whenever achieving that can be achieved for a given alpha if you supply certain g and that g value if you are just represent here g threshold just here you put g threshold for g = g threshold you can get this one equal to 1 that is what we have written here.

So, that means g threshold is the definition of the gain of the gain coefficient required for which a round trip gain will be 1 gain g threshold is the gain coefficient you are activating after supplying pump into the waveguide laser active wave guide then one round trip the intensity or power gain will be just 1 that is remember that this is a power gain but g threshold we are consider threshold gain coefficient.

So, that gain coefficient can be controlled, the value of the gain coefficient can be controlled with the pump power level pump here. So, it is actually it can be controlled basically externally depending on your pump supply. So, now from here you can find out g threshold equal this this expression and normally this alpha we know that is actually your loss coefficient and this one we can think of this thing this is the loss because of the 2 mirrors.

And you are dividing it by 2L that means, that division 2L means that means your mirror loss which is actually lump losses here and here happening when propagation when the signal goes here at this lump point at one particular spot where you are losing something and then comes back and again because of the mirror here you are losing not completely reflected. So, that loss is this one total loss per tool reflection.

And that has been divided by 2L meaning you have distributed that you are just considering that one as a per unit length, whatever the mirror you are just distributing the mirror loss into the entire cavity. So, in that case that we are writing like the alpha m mirror loss distributed mirror loss that means, instead of just lump loss, we are considering that per in per unit length, how much loss coefficient is there.

So, this is actual alpha total that means, that g threshold that means gain coefficient gain coefficient must be exactly equal to the alpha coefficient the loss coefficient total loss coefficient one is a waveguide loss coefficient contribution coming from waveguide loss coefficient and another is the mirror loss coefficient then, that time you can say that one round trip you are not loosing anything you are just withstanding your field amplitude.

But now, if you g is greater than g threshold that means, your E 1 will be must be is greater than E naught. So, when E 1 must be is greater than E naught what happens that additional field whatever will come here that will give you some more energy that overcoming the loss and that overcoming when it is overcoming the loss that means it will start growing energy inside the cavity and when it starts growing the energy inside the cavity.

Then you see because that energy growth how much that depends on your quality factor gain etcetera, and it will come to a steady state for a given g value. It will come to a steady state where internally sum energy will be stored and that fraction of the energy must be coming out because this mirror is not 100% reflectivity that fraction of energy coming out that will be exhibiting as a laser. That is what actually very briefly and a simplified way I have explained how a laser emission can happened.

That is actually explained more detail in any laser physics book you can go through that, but here I have just discussed constituting the mirror and mirror integrated into the waveguide and you have such certain kind of pump.

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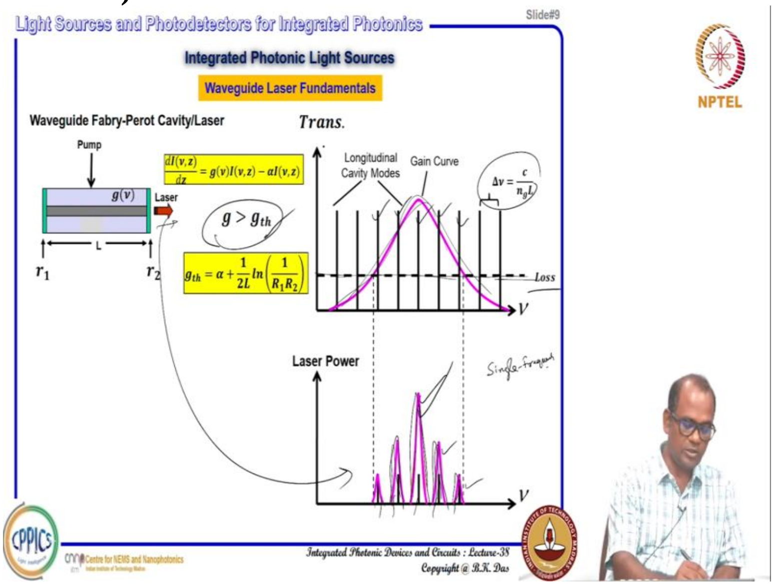

Light Sources and Photodetectors for Integrated Photonics

Slide#9

Integrated Photonic Light Sources

Waveguide Laser Fundamentals

Waveguide Fabry-Perot Cavity/Laser

$\frac{dI(\nu,z)}{dz} = g(\nu)I(\nu,z) - \alpha I(\nu,z)$

$g > g_{th}$

$g_{th} = \alpha + \frac{1}{2L} \ln\left(\frac{1}{R_1 R_2}\right)$

$\Delta\nu = \frac{c}{n_g L}$

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So, that actually represented here. So, this is the loss here is a loss coefficient suppose you are considering when g threshold exactly equal to loss up to here. So, you do not see anything output here, but when this g is greater than g threshold as I mentioned for example, if your gain curve with respect to this one this is this thing and your loss curve it is here like this, this is the dust line this is your loss level we are considering the loss is actually frequency independent.

But gain is frequency dependent, then what we see that these frequency these frequency this frequency this frequency these 5 frequencies it seems gain which is actually overcoming the loss meaning those pi frequency will see gain and it will overcome the loss of the cavity and that can come out as a laser. So, if you just see the spectrum of the laser when g is greater than g threshold.

You will see all longitudinal modes depending on the gain profile; you see the longitudinal most will be which will be higher and which will be lower which will be smaller and so on. Typically, if you see any Fabry-Perot laser depending on the length etcetera, you can see they will be distinct frequent there will be distinct frequencies the in the laser spectrum though we call it a laser is a monochromatic light source but indeed it is not monochromatic.

There is a fine features are there they are separated by longitudinal modes. Normally if multiple longitudinal modes are there in the laser emission, they are not good for precision application communication etcetera. So, it is always good to have a laser to oscillate only in one longitudinal mode when a laser oscillates in one longitudinal mode that is called single frequency laser single frequency laser. How that is possible.

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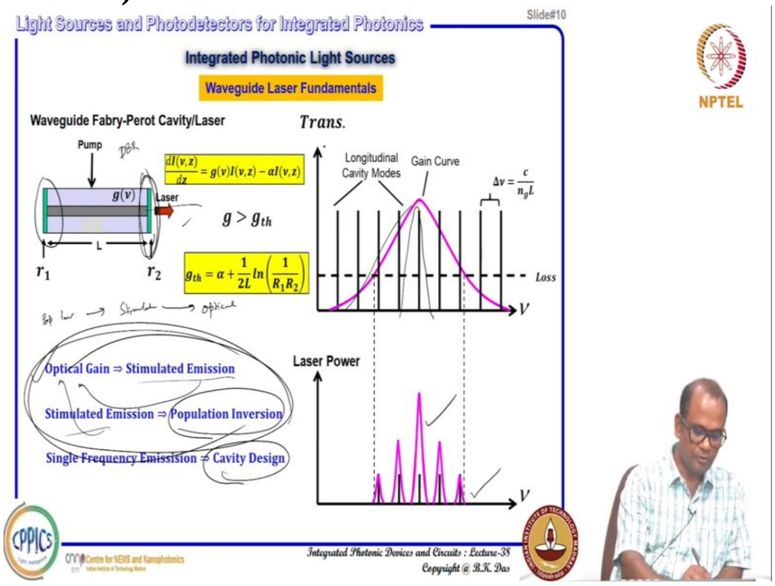

Light Sources and Photodetectors for Integrated Photonics

Slide#10

Integrated Photonic Light Sources

Waveguide Laser Fundamentals

Waveguide Fabry-Perot Cavity/Laser

$$\frac{dI(\nu,z)}{dz} = g(\nu)I(\nu,z) - \alpha I(\nu,z)$$

$g > g_{th}$

$$g_{th} = \alpha + \frac{1}{2L}\ln\left(\frac{1}{R_1R_2}\right)$$

Optical Gain ⇒ Stimulated Emission

Stimulated Emission ⇒ Population Inversion

Single Frequency Emission ⇒ Cavity Design

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Obviously, I have just listed here I am not going into detail, but I can give you some kind of overview how to get that. So, what I have discussed here optical gain actually that is coming through stimulated emission, for example, that thing you can I think within the scope of this course, I cannot discuss that in much detail, but stimulated emission that means, actually if you have one photon and if you have a population inversion.

Then that 1 photon will start help emitting another photon of its own property. So, 2 photons will be generated 2 photons will be again stimulates into 4, 4 will be stimulates again 8, 8 into 16 and so, on it will be cascaded effect will be there and you can see a gigantic amount of intensity or power of that same frequency in the same direction and that is called stimulated emission.

And this stimulated emission basically stimulated emission causes optical gain and normally where from stimulated how stimulated when stimulated emission happens when there is a population inversion. So, this population inversion is also again very well known in laser physics, but I will be discussing here how this population inversion population what it means, in a semiconductor laser diode and that population inversion how you can create.

How can achieve and how that population inverse help per stimulated emission and that stimulated emission again give rise to result into a optical gain, that thing is the whatever this I discussed that as the internal physical makeup effects internal physics of any laser cavity, how you are designing your waveguide active material medium, what is the pumping system, all those types of things involves this starting from population inversion to stimulated emission to optical gain.

So, I can see that I can picturize that first you get a population inversion in a material medium that will give you stimulated emission and that will give you basically optical gain and optical gain if you have a positive feedback like a mirror like that and this gain is sufficiently higher than the loss of the cavity then you get the laser that is the overall principle of a laser emission.

But, as I say that is simple Fabry-Perot cavity you can have multiple frequencies, but how to active single frequency that actually depends on your cavity design, cavity design means how you are designing your mirror, how is your gain curve suppose your gain curve is very narrow somehow then only one longitudinal frequency only it will see the gain. So, that will be actually edging.

Otherwise indirectly what you can do this mirror which is giving a positive feedback reflection to all frequencies you can design this mirror for example using a DBR distributed Bragg reflector where your reflection happens only within a narrow band narrow frequency range. So, that narrow frequency range reflection will give you positive feedback all other frequencies that will be passing so that will not build up. So, in that case you can achieve also single frequency lasers.

So, that much is good enough for this course. I think if you want to know much more details how one can achieve single frequency laser so any textbook you can just consult and it is not so difficult to understand also.

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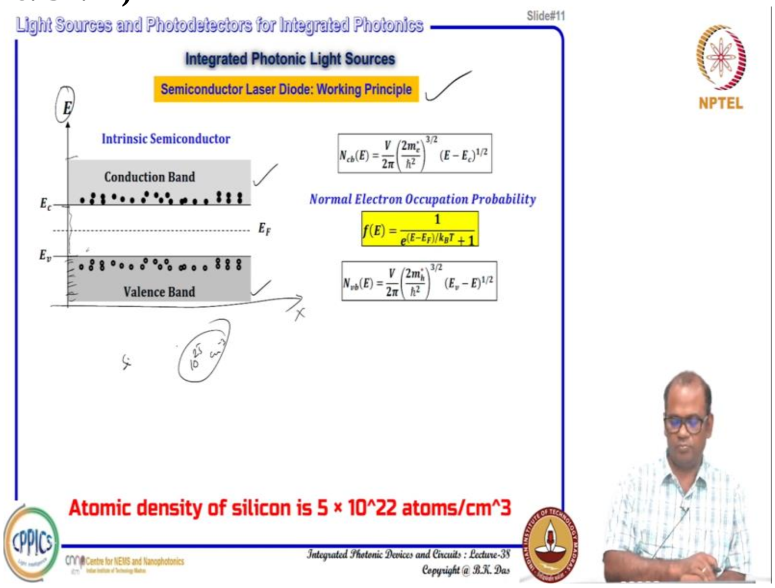

Light Sources and Photodetectors for Integrated Photonics

Slide#11

Integrated Photonic Light Sources

Semiconductor Laser Diode: Working Principle

Intrinsic Semiconductor

$$N_{cb}(E) = \frac{V}{2\pi}\left(\frac{2m_e^*}{\hbar^2}\right)^{3/2}(E - E_c)^{1/2}$$

Normal Electron Occupation Probability

$$f(E) = \frac{1}{e^{(E-E_F)/k_BT} + 1}$$

$$N_{vb}(E) = \frac{V}{2\pi}\left(\frac{2m_h^*}{\hbar^2}\right)^{3/2}(E_v - E)^{1/2}$$

Atomic density of silicon is 5 × 10^22 atoms/cm^3

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Now, now as I mentioned, we will be discussing about semiconductor laser diode working principle that is actually most important for our photonic integrated circuits and today whatever photonic integrated circuits we are implementing and commercial level it will also the semiconductor laser diodes are basically integrated on chip or it can be used off chip and board level etcetera.

So, to understand a semiconductor to discuss a semiconductor again, it is a huge topic. There are textbooks are available only for a semiconductor lasers, light emitting diode as well as lasers etcetera. but here I will be just giving you an overview, which is actually which may helpful for you to understand that what are the limitations particularly for photonic integrated circuit applications for integrating different types of lasers and how one can proceed to improve it etcetera.

Let us consider semiconductor, if you just see simple band structure on band structure of any semiconductor normally we see that in any textbook if you see there is a conduction band there is a valance band and conduction band and valence band whenever it is shown like that you can consider this x axis is just a position at any position you go you can see that electron will have certain up to certain band it is allowed energy levels are there band of energies are allowed.

That means electrons can occupy that energy this is energy axis and then again there is a gap band stop band where electrons is not allowed those energies are not allowed for electrons and then again you can find another band of energies and electron can be allowed to occupy those energies accept those energies and in this way any crystallographic structure any solid state semiconductor dielectric or whatever, if it is a crystallographic structure is there.

Because of the periodic arrangement of atomic atoms or molecules actually gives some kind of periodic potential for electrons and that periodic potential if you solve using quantum mechanics like it is Illingworth equation etcetera, and different methods are there then you can see that electrons actually can accept only a certain band of energies and certain band will not be occupied that will called it stop band.

So, valance band is the band particularly per semiconductor that is the band where at low temperature all energy levels are occupied and they are immediately after what there is a gap and above that there is another band of solutions you can get but electrons will not be occupied because there are no excess electrons. So, all the electrons are occupied here somehow for example.

But in this case it is shown that some open circles if you see that that means some of the electrons are somehow missing at room temperature what happened some electrons they will interact with each other and scatter each other and they can actually jump into the conduction band they acquire some energy and go to the conduction very little bit amount of electrons can be available in the conduction band.

That is what we know as a semiconductor any semiconductor if you see for example, if you see silicon, silicon normally your atomic density in a crystal that will be about 10 to the power 25 per centimetre cube or so, 10 to the power 25, 10 to the power 26, I think 10 to the 25 per centimetre cube atomic density, but, you know each of these silicon has a 4 valance electrons.

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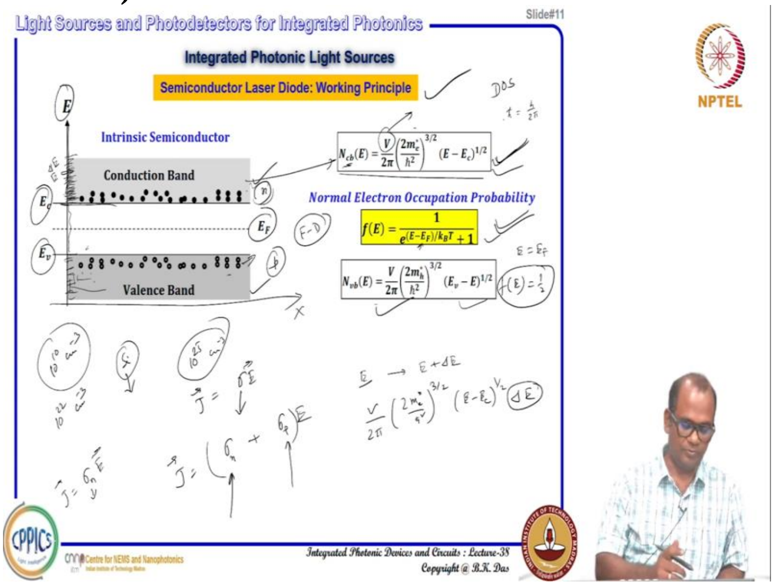

Light Sources and Photodetectors for Integrated Photonics

Slide#11

Integrated Photonic Light Sources

Semiconductor Laser Diode: Working Principle

Intrinsic Semiconductor

Normal Electron Occupation Probability

$N_{cb}(E) = \frac{V}{2\pi}\left(\frac{2m_e^*}{\hbar^2}\right)^{3/2}(E-E_c)^{1/2}$

$f(E) = \frac{1}{e^{(E-E_F)/k_BT}+1}$

$N_{vb}(E) = \frac{V}{2\pi}\left(\frac{2m_h^*}{\hbar^2}\right)^{3/2}(E_v-E)^{1/2}$

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Those 4 valance electrons actually contributes or occupy all these valance band. Now, it can happen that because of the energies thermal excitation etcetera. So, those few of them electron can go up we see that normally at room temperature a silicon crystal intrinsic silicon crystal where nothing no defects, no doping etcetera, is there in the order of 10 to the power 10 centimetre cube per centimetre cube, number of electrons can be available in the conduction band.

So, when 10 to the power 10 per centimetre cube electrons are available in the conduction band, some little amount of conductivity in the conduction band at the same time the empty spots here they are called holes they are can be also big, they can also allow some valance band electrons to move in because there is some kind of empty spaces are there they can actually hop one atom to another atom some kind of mobility they will get.

So that is the way a semiconductor is actually distinguished from the metal how because here in this case conduction band you will get certain kind of electrons some number of electrons and valance band also some number of empty and some electron has some kind of issue some apply some kind of electric field. So, this this empty can empty spots empty points they will they can also move.

So, that that can be carrying some kind of current and also conduction band electrons also can carry also current suppose you have a n carrier electron density in the conduction band and p is the electron density hole density so, called empty spots density in the valance band both n and this holes so, called holes they contribute to the current conduction, current conduction means, you know the j current density is sigma times E j is the current density.

So, this sigma again you can consider that can be corresponding to a sigma n that means, electrons in the conduction band and holes in the valence band and both actually contributes for the current. So, that is how we can define, but, in case of conductor normally you do not have such situation you have only highest band you will see that pump it is not completely filled.

So, some empty energy levels are there that is the reason that that highest band that means this conduction bands to itself it has some empty spots like a lot of energy levels are free. So, electronic to apply energy electron can acquire some energy and can become mobile and it can have a conductivity good conductivity normally you have 10 to the power 22 per centimetre cube free electrons in the conduction band.

So, that many number of electrons actually contributes for the sigma. So, if it is a conductor now, that in that case only sigma n that is actually the current density you can that means current conduction current actual contributed by electrons only so, that is the difference in the semiconductor and conductor. But in case of semiconductor you can by doping by doping you can actually change this n electron free electron in the conduction band.

And or hole in the valence band and depending on that you can actually enhance the contribution of sigma n or hole together or individually. So, that way actually we can control the conductivity of a semiconductor. That is why it is very much important particularly for electronic industry that I think that is not the thing I am going to discuss I will be just taking the important aspects what is necessary for this course.

For this chapter of this course, again one more interesting thing if you see that here, this energy, energy levels I say that they are allowed energy levels they are continuous we said but actually they are not continuous, they are actually fine features fine lines are there. So, they are spaced, but they are spacing energy levels their spacing are so, close that you can consider like a continuous.

And if you see that, the number of lines the energy states available that can be shown that that can be expressed in terms of this one in the conduction band cb is stands for conduction band where E c is the bottom of the conduction band energy level energy that is actually defining bottom of the conduction level and E v is the top of the balance band here it is shown. So, in the conduction band, if you see that the number of energy states available per unit of energy.

Suppose you have considered delta E this is your E this c above E c you are just considering at a certain value of E at a particular point. What is the number of density number of energy levels available at E. That actually can be expressed in any solid state physics book you can find that it is that can be expressed by this one where this V is the volume of your substrate your material you are using.

If, if you remove this volume that means per unit volume you can normalise density of states we call it as a density of states and to m is the m star is the effective mass of the electron in the conduction band and h bar means it is a reduced plank constant nothing but h / 2 pi and E by E – E c 2 square root. So, that means, as you increase the energy, your number of energy levels will be increasing.

So, for example, if you are considering at E, you are considering E from E to delta E what how many number of energy levels are available to occupy it, so, that electron can occupy then you can say that this one 2 pi 2 m star h bar square 3 by 2 E – E c times delta E. So, that means, at E per unit increment of energy the number of allowed energy levels can be computed by this expression E – E c.

That means, it this will be always a positive value. Similarly, for the valance band same thing, but you know here it is a whole empty so, electrons will see different type of situation. So, here we call it effective mass of the electron energy effective mass of the hole where is the positive charge that means, the missing of the electrons we can consider like a positive charge and effective mass m star.

Similar expression but instead of E – E c E v - E because here energy all the allowed energies are less than E v that is why E v less than E so, we need to have some positive value so, we get this table. So, this is the energy levels available. Now, another interesting thing I think you all know that at a given energy and for a given temperature what is the occupation probability? What is the probability of occupancy per an electron?

That is actually defined by Fermi-Dirac statistics. So, energy levels available does not mean that energy they are electrons is already occupied that occupation probability actually depends on your temperature because normally we know at to low temperature entire valence band is completely occupied. Now, if I want to see that I am raising the temperature so, then the electrons can go to the conduction band and any energy levels available.

They will try to occupy and that occupation probability actually predicted by the actually it follows a normally Fermi-Dirac distribution and that expression is this one where we have defined another additional energy level called Fermi energy level. So, Fermi energy level according to this expression you can consider when E = E F that means, f E will be equal to half so, occupation probably that is the energy level we define as a reference energy level will define where occupation probabilities is a half.

So, sometimes it is called actually chemical potential, but in semiconductor it is mostly known as a Fermi energy levels. So, energy levels available and they are how many electrons can be occupied that also can be expressed this one these all these are explained very detailed in any of these solid state electronics device book but, I just as I mentioned earlier that this may be helpful for understanding semiconductor laser also.

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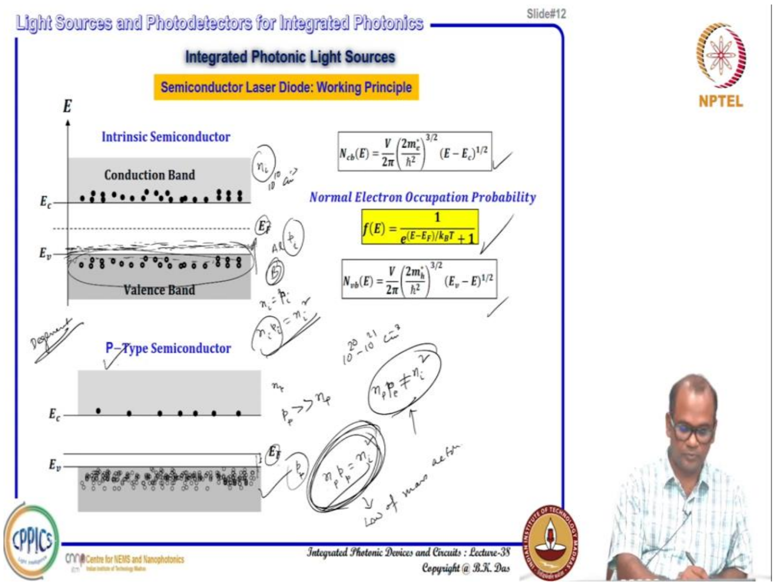

Light Sources and Photodetectors for Integrated Photonics

Slide#12

Integrated Photonic Light Sources

Semiconductor Laser Diode: Working Principle

$$N_{cb}(E) = \frac{V}{2\pi}\left(\frac{2m_e^*}{\hbar^2}\right)^{3/2}(E - E_c)^{1/2}$$

Normal Electron Occupation Probability

$$f(E) = \frac{1}{e^{(E-E_F)/k_BT} + 1}$$

$$N_{vb}(E) = \frac{V}{2\pi}\left(\frac{2m_h^*}{\hbar^2}\right)^{3/2}(E_v - E)^{1/2}$$

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So, now, as I mentioned suppose, if you are considering P type semiconductor P type semiconductor means, you doped some things such that that doping level you are just considering some atom like aluminium you are doping in silicon for example, aluminium is a trivalent metal. So, aluminium or maybe you can consider like so called boron. Let us consider boron.

Boron is also trivalent material. So, what happens, the fourth electron fourth electron if this boron is actually occupying some of the silicon sides, the fourth electron is looking like a boron will be behaving like a silicon but fourth electron missing fourth electron you can consider this boron is something like a silicon tetravalent material silicon has a 4 valance electron here 3 electrons.

So, those 3 electron this third electron defects states created here, once it clears here, so, lots of electron can get a little bit of energy, thermal energy and can occupy this space. So, you can get a lot of holes created in the valence band a lot of holes will be created in the valence band meaning electrons are going a little bit up. So, when electrons are going a little bit up, then occupation probability were actually supposed to get half occupation probability.

That Fermi me energy level will pull down downward. So, P type semiconductor you can have a lot of holes that can be conductive, but valance band itself because of the hole it starts conducting and you can see that normally here in case of intrinsic semiconductor I say that some level of 10 to the power 10 for example, in silicon 10 to the power 10 per centimetre cube atoms or electrons are there in the conduction band.

But whenever you have a doping P type, normally majority of electrons will be just dropped in this defect level. So, in the conduction band you would not see much. So, the n value here it was n here and it was a p here, number of intrinsic concentration, whole concentration p i. Now, if it is doped like that, this is n whatever the concentration and this will be your p. So, we can consider P type means P type doping is there we can write like this P p and P p.

That means, n is the concentration of electron per P type doping and P p is the hole concentration for the P type doping normally in this case P p will be much higher than n p, but in this case n i = p i normally n i and p i that is actually = n i square, but when this even though it this is happening here you will see that n p and p p that also = n i square. So, normally this is actually this can be shown in any using your all the principles or the distributions.

And energy density etcetera, you can show that whatever the situation whether you dope or not that the carrier concentration electron concentration in the conduction band and hole concentration in the valance band that will be actually equal to n i square normally they are equal and n p even though your hole concentration you have increased simultaneously your electron concentration in the conduction band will be reduced.

And such that this thing will be followed that means total multiplications should be n i square that is actually known as the law of mass action in well known in semiconductor devices. So, this is actually true this thing actually true as long as the doping level is moderate. So, normal you know doping level you can go up to say 10 to the power 20 to 10 to the power 21 per centimetre cube.

This type of doping concentration we can achieve. So, normally if you dope more heavily doped so, what happens as I mention this defects level for example, whatever I am considering, if you keep on doping more and more than this defects level also it will be like it will not be like only one line it will be like a broadening. So, these defect lines also keep on broadening, broadening and then what you see that will also penetrate inside.

Because of the doping of boron or etcetera, those energy states will be penetrated inside into the valance band also. So, in that case you can see originally there were energy states and now additional doping that will create additional states inside that means you may get a multiple solutions in same level energy level that type of semiconductor is called degenerate semiconductor.

In degenerate semiconductor, this Fermi level can happen that can push inside the valence band for P type in that case, since the energy additional energy levels penetrated inside the valence band. That is why it is degenerate semiconductor and that is the reason you will find that that this n p and P p that will not be equal to n i square in that case in case of degenerate semiconductor this law of mass action will violates.

Because your defect actual that will modify your energy bands that will create some kind of degenerate energy states within the band that is why they are called degenerate semiconductor and I can tell you that if you want to get a semiconductor laser, one of the major condition is that your semiconductors must be heavily doped such that Fermi level can be penetrated deep inside to the valance band or conduction band.

I will shown for this P type semiconductor N type semiconductor also identical situation the Fermi level can push inside the conduction band. So, in that case degenerate semiconductor required and that situation you will have this type of situation also law of mass action it will not follow the law of mass action and that is actually one of the important requirement for the semiconductor I will be discussing very quickly.

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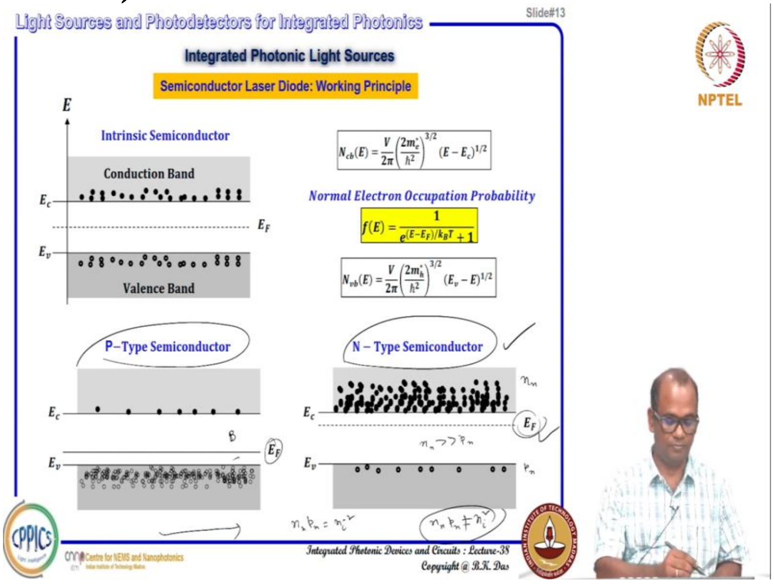

Light Sources and Photodetectors for Integrated Photonics

Slide#13

Integrated Photonic Light Sources

Semiconductor Laser Diode: Working Principle

Intrinsic Semiconductor

$$N_{cb}(E) = \frac{V}{2\pi}\left(\frac{2m_e^*}{\hbar^2}\right)^{3/2}(E - E_c)^{1/2}$$

Normal Electron Occupation Probability

$$f(E) = \frac{1}{e^{(E-E_F)/k_BT} + 1}$$

$$N_{vb}(E) = \frac{V}{2\pi}\left(\frac{2m_h^*}{\hbar^2}\right)^{3/2}(E_v - E)^{1/2}$$

P–Type Semiconductor

N – Type Semiconductor

$n_n >> p_n$

$n_n p_n = n_i^2$

$n_n p_n \neq n_i^2$

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Now, this is the N type similarly, N type semiconductor, so, whenever you are doping you are in n n and here you can get p n. Now, in this case again we can say that n n is much much greater than p n now and if it is moderately doped then n n and p n should be equal to n i square, but if it is degenerate semiconductor n n and p n not equal to n i square intrinsic semiconductor.

So, these all these are very basics for semiconductor and for degenerate semiconductor which is very important for our laser emission I will be discussing that. Now let us see, if you are creating a PN junction what happens if it is a PN junction just remember that if this is P type semiconductor and this is your N type semiconductor and suppose you have a material in one section you are just having a P type semiconductor another section is N type semiconductor what happens.

So, you see because this is same material one side you are doping with a P type like a boron and another maybe you are doping like a phosphorus where pentavalent material is doped so, that a lot of electrons are their Fermi level here, you see, one side Fermi level is lower another side Fermi level is higher, but you know in a semiconductor it is a continuous the as you go as a function of x.

You cannot say that the probability occupation probability for a particular energy states at the inside will be somewhere here E F lower region and occupation probability half here will be higher that cannot happen what happens the electrons here will try to move towards the P side and holes will try to move towards the N side that will continue as long as this Fermi level from the both side will be align.

So, in that case, this entire conduction band in the P side and balance band and conduction band balance when this side they will start bending like that, that is what it is shown here.

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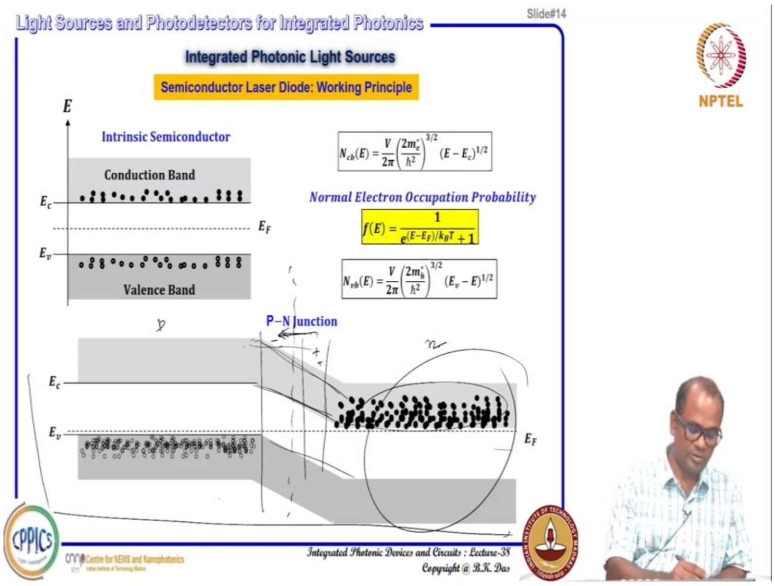

Light Sources and Photodetectors for Integrated Photonics

Slide#14

Integrated Photonic Light Sources

Semiconductor Laser Diode: Working Principle

$N_{cb}(E) = \frac{V}{2\pi}\left(\frac{2m_e^*}{\hbar^2}\right)^{3/2}(E-E_c)^{1/2}$

Normal Electron Occupation Probability

$f(E) = \frac{1}{e^{(E-E_F)/k_BT}+1}$

$N_{vb}(E) = \frac{V}{2\pi}\left(\frac{2m_h^*}{\hbar^2}\right)^{3/2}(E_v-E)^{1/2}$

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You see this is the Fermi level try to align and this side in the conduction band this is the N side and this is the P side P side if you see no electrons are there in the conduction band almost maybe scattered 1 or 2 will be there and N side the lot of electrons in the conduction band, but no holes in the valence band in the N side this vice versa Fermi level is align like that, this is the standard.

Whenever you are fabricating a PN junction and if you see at any position this is this can be your so called metallurgical junction. So, this type of bend banding happens because you know that the electron will move this side then this side you will get some kind of plus immobile atoms will be there and this side it will be negative sign will be there because once electron moves this side from this side to this side.

Then what happens originally because even though a lot of electrons are right there in the conduction band a lot of holes are there in the valence band as a hole any N type material or P type semiconductor material they are neutral, but what is happening here because of the Fermi level alignment some electron moves that means certain region you will see that this positive charge is created this side it will be negative charge will be created.

So, that negative charge and positive charge will be created. So, in that case, you will see some kind of electric field like this. So, when electric field is this one then what they will do this electric field actually meaning that means, the potential energy for the electrons will be different. So, energy band will be like bent like this thing any semiconductor device book these are known.

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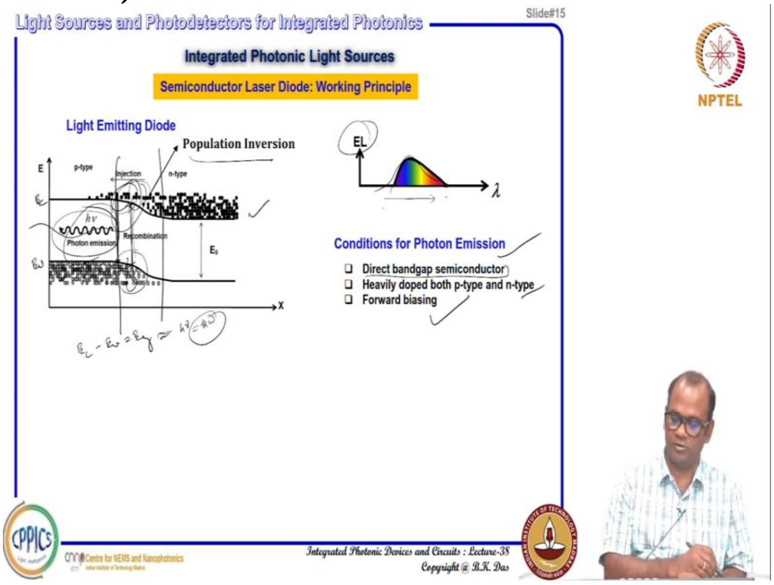

Light Sources and Photodetectors for Integrated Photonics

Slide#15

Integrated Photonic Light Sources

Semiconductor Laser Diode: Working Principle

Light Emitting Diode

Conditions for Photon Emission

- ❑ Direct bandgap semiconductor
- ❑ Heavily doped both p-type and n-type
- ❑ Forward biasing

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Now what happens light emitting diodes suppose you have a heavily doped semiconductor P type and N type that means degenerate semiconductor so, that Fermi level is more closer to the conduction band and the N side and closer to the valance band in the P side and you are giving a so, called what to call that forward bias you just go back forward bias then what happens you are this is already electric field is there and this is whatever the band bending that is called actually built in photon cell potential.

So, energy differences q times qv now, whenever you are giving a some something you are connecting here positive here and negative here then what happens then this built in photon cell will start reducing and then what happens your some electrons can move into the conduction band towards the P side and holes also moves into the transplant. So, this is the situation where actually you apply some power bias.

And then you create it you generate are somehow kind of additional electrons in the conduction band in this depletion region and additional holes in the depletion regions that you can create it across the depletion region that is actually called population inversion that is somehow you are actually forcing your distribution not similar to like a Fermi-Dirac distribution it is something against the normal inversion a normal population of the electrons as a function of energy.

And it is somehow we call it as inversion population inversion. So, when this population inversion happens, you can imagine that in this region that lot of electrons are there in the conduction band and a lot of holes are there in the valence band, which is actually against the normal population distribution. So, what happens natural tendency what would be there this electrons from the conduction band comes back to the valance band and they combined with the hole.

And the when it combined with the whole it will, loose some energy that energy will be can be radioactive energy like electromagnetic wave but photon will be one photon and regenerated and that is a natural process spontaneously it can happen this spontaneously when it is happening that photon will be there and back photon can be considered if you can have large number of electron photon recombination happening large amount of photons will be coming out and you can see something like a light source.

But one thing is that it is not the that the you are creating population inversion and then in the depletion region because of the forward bias and photon will be coming out sometimes normally, we will see that in the next lecture I will show that this is not always true that if you are just creating just giving a forward bias and even if it is a degenerate heavily doped. It cannot be always true that electrons will recombine to the hole and emit a photon.

Instead what we will do that there these electrons will try to come down to the valance band but with a different path non-radioactive path, it will loose some energy to the crystal to the photons and it will heat up the material but no photon that is happening in certain type of semiconductor like silicon itself. That never happens this type of photon emission. So, condition for photon emission is you needed direct bandgap semiconductor which is silicon is not a direct bandgap semiconductor.

And you will need a heavily doped both P type and N type to make a junction PN junction and you will need a forward biasing then, when electrons and photons combines the energy if you see the separation. That is actually this E c and this is E v that means E c – E v = E g that is called bandgap. So, when photon comes out the photon energy should be around h nu or it is h cot omega you can say that h cot omega.

So, this photon it, it does not mean that electrons coming from the bottom of the conduction band and just recombining at the bottom at the top of the valence band, it can have certain kinds of distribution. So, you can have a photon energy with a lot of distribution this is your lambda or omega, whatever you can consider this is electroluminescence. So, you will get a spectrum broad spectrum.

So LED spectrum even though if you see blue LED or green LED whatever available today red LED, but it will have a certain window rate what it is not one wavelength it will have certain kind of spectrum that has some range you will be getting also emission.

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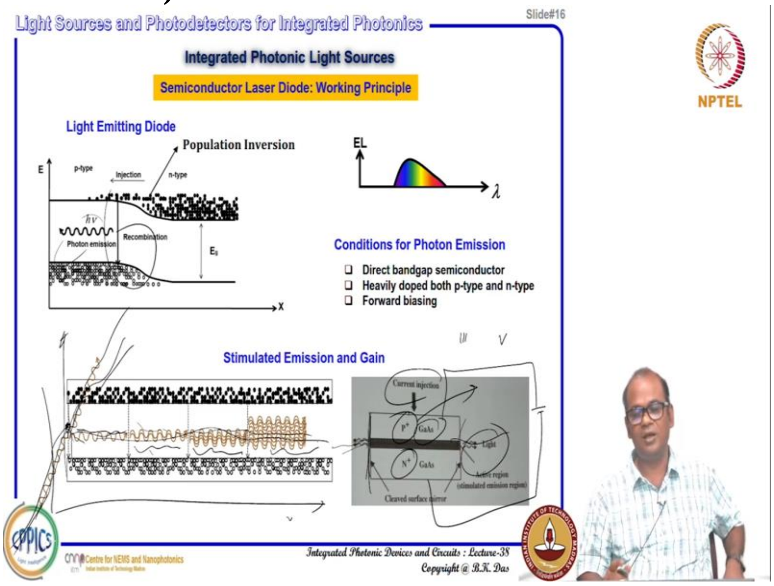

Light Sources and Photodetectors for Integrated Photonics

Integrated Photonic Light Sources

Semiconductor Laser Diode: Working Principle

Light Emitting Diode

Conditions for Photon Emission

- ☐ Direct bandgap semiconductor
- ☐ Heavily doped both p-type and n-type
- ☐ Forward biasing

Stimulated Emission and Gain

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Now, what do you see that one photon if it is a emitting for example, you consider a particular point this is your energy this is your x at any position at a particular point, you can see that one electron is just combined to the hole and a photon can emits it can emits it can go in this direction, it can go in this direction it can go in this direction, it is a 3 dimensional option freedom is there even though it is showing energy scale at any point any photon is emitting it has options to travel in all directions.

But what happens it can happen you consider a certain direction it is moving for example x direction while moving if it sees that one more electron being because of the dipole oscillation certain kind of dipole of oscillation that dipole stimulates again another electron to de excite and then you can get 2 photons, 2 photons again helps to generate 4 photons, which are actually stimulated emission can happen.

But this stimulated emission should not be lost again whatever emitting the photons that should not be lost, you should create a certain kind of situation so, that these photons are not reabsorbed again this should come out of this material. So that you can get a good light from a light emitting diode, for example it is shown here it has been created certain gallium arsenide, gallium arsenide is a compound semiconductor you know gallium from the group 3 and of the periodic table and arsenic from the group 5 or the periodic table.

If you can make a compound semiconductor like this, they are basically direct bandgap semiconductor that means, electron I will just explain what is direct bandgap and indirect bandgap semiconductor in the next lecture, but for the moment you just understand that gallium arsenide is a direct bandgap semiconductor you have a p plus doping p plus means heavily doping to get degenerate semiconductor n plus doping heavily doped to get a degenerate semiconductor.

And then if you give a current injection that means, you are giving a forward bias like this then your electron hole recombination takes place and you get energy photon output. So, this from the output you can get this can be clipped surface this is semiconductor clipped surface, but clipped surface you know this whenever coming you can get certain kind of reflection here certain kind of reflection here because of the panel reflection.

So, you can think some kind of feedback mirror is there. So, ultimately you may get some kind of laser light whatever I have discussed earlier, but at the same time, when it is propagating in this direction as I mentioned that photons should not move other direction even if it is going other direction that direction should be lost in a certain direction when it is propagating it should be accumulated or should be confined.

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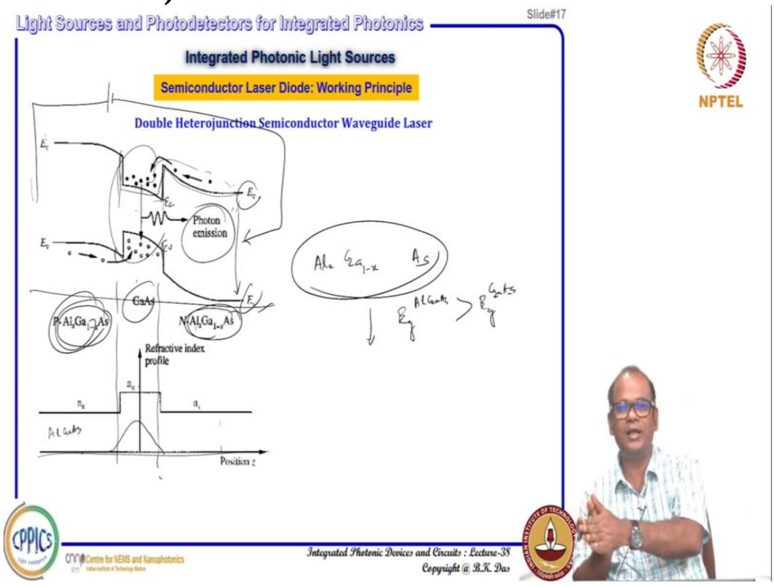

Light Sources and Photodetectors for Integrated Photonics

Slide#17

Integrated Photonic Light Sources

Semiconductor Laser Diode: Working Principle

Double Heterojunction Semiconductor Waveguide Laser

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So, for that purpose what it is done people demonstrate it a double heterojunction semiconductor what it is done. For example, if you have one side is so called aluminium gallium arsenide and another side aluminium gallium arsenide that means, you know gallium arsenide this is gallium arsenide. So, what, they are doing the extraction of gallium is replaced by aluminium certain number of gallium atoms are replaced by same number of aluminium atoms.

So, in that case if you make such kind of compound alloy, then you will see that the bandgap will go up E g for AlGaAs is greater than E g per gallium arsenide. Now, you see this side AlGaAs this side AlGaAs this is E c this is E v this is your bandgap for the gas and in between you have gallium arsenide this is E c for the gallium arsenide this is E v for the gallium arsenide and if you make a junction here you see there is a clear cut step in E c.

E c curve you see clear cut step here. Similarly, this side also you will see, I will guess will be like this and this type of things there. So, now, in this region if you see if you are giving a suppose this side if you are giving this P type doping and this side N type doping and you are giving suppose forward bias and this side you are connecting here like this negative bias so, electron can move.

So, electron from this AlGaAs side N side it moves and when it comes here it looks like a quantum well it can stay a little longer and holes from this side it come here it goes here it is all hope per hole also, you will see some kind of quantum well, so, it can stay a little bit longer time it can accumulate it gets time electron gets time to combine to the hole. So, you get a you are enhancing the photon emission.

So, that means you can in the depletion region active region you are creating some kind of confinement of per both electrons and holes whenever you are going followed wires suppose this is x direction, but at the same time one advantages situation came what is that when bandgap is reduced for compound semiconductor, the refractive index is in normal increases. So, this is the AlGaAs side for example.

Up to here refractive index is lower this is the AlGaAs side refractive index is lower position and gallium arsenide side refractive index is higher you can imagine lower refractive index, high refractive index lower refractive index. So, light can also confine here in this region. So, light can confine so, let me see this one like this light can confine here like this. So, that means, you can have you can maintain this type of structure in a particular direction.

So, light can actually confine along that direction electron hole pair will be there population inversion will be there and you can have a guided mode also even 1 deacon confinement you can have. So, as it propagates more stimulated emission will happen. So, you get optical gain.

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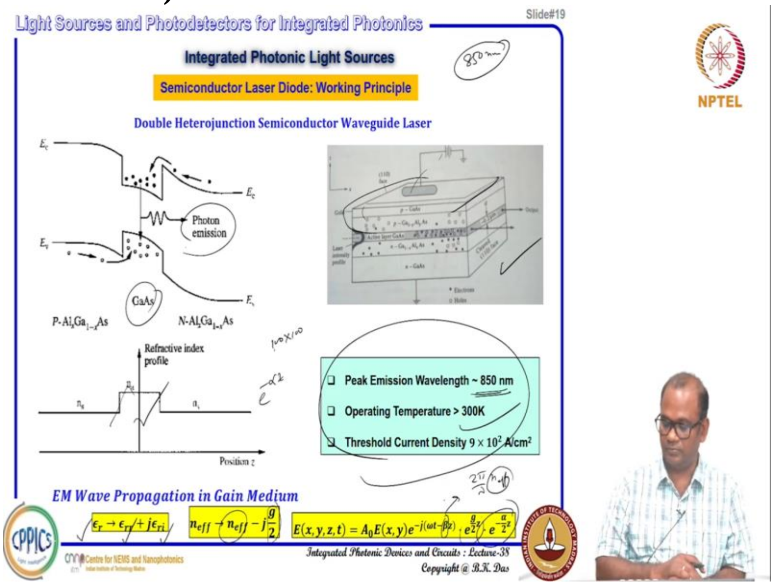

Light Sources and Photodetectors for Integrated Photonics

Slide#19

Integrated Photonic Light Sources

Semiconductor Laser Diode: Working Principle

Double Heterojunction Semiconductor Waveguide Laser

☐ Peak Emission Wavelength ~ 850 nm

☐ Operating Temperature > 300K

☐ Threshold Current Density 9×10^2 A/cm^2

EM Wave Propagation in Gain Medium

$\epsilon_r \to \epsilon_{rr} + j\epsilon_{ri}$

$n_{eff} \to n_{eff} - j\frac{g}{2}$

$E(x,y,z,t) = A_0 E(x,y) e^{-j(\omega t - \beta z)} \cdot e^{\frac{g}{2}z} \cdot e^{-\frac{\alpha}{2}z}$

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And this is the situation it is shown here, this is P type doped AlGaAs N type dope AlGaAs and in between actively or gallium arsenide you can see here and you are giving a forward bias here inside is grounded here. So, you can see that your electrons are being injected, holes will be injected from this side electrons will be injected from this side and then the combination happens because of this type of quantum well and then laser intensity.

That means this is actually shown as a guided mode for example, we have shown earlier it is one waveguide it is shown here. So, light will be confined here and you can get a laser source here though it is just 1 dimensional confinement you can have will show that there is a situation so, technology available today also you can confine the other side also you can have a hole region only active region all around you can have a aluminium gallium arsenide.

So, you can get a 2 dimensional waveguide where you can actually create so, called population inversion like this electron and hole can be also confined because of the forward bias in the active region and then it can be optical waveguide also so, as you photon emit it can propagates in a certain direction and it can amplify and you can have a mirror you can get n medium and you can get laser also.

So, for this type of laser early in 1970s 60s people demonstrated that the emission because gallium arsenide bandgap whatever the bandgap it is emission that emission actual supports 850 nanometre wavelength that was the first efficient laser source demonstrated and operating at room temperature and threshold current this threshold current if you whatever the current is there if you just divide it into area than threshold current density.

We can call it ampere per centimetre 9 into that means 900 ampere per centimetre square very large amount per centimetre square if you want to have a 1 centimetre by 1 centimetre laser diode normally not, so then you need 900 ampere huge this type of current cannot supply really. So, instead of that what you can do here, device size device area this area can be in the order of some 100 micron / 100 micron for example.

So 100 micron / 100 micron then you can bring it down your threshold current maybe 2 ampere level. So, this is the thing first efficient semiconductor lasers operating at room temperature available in the market and that is the reason when fibre optic communication started the first generation fibre optic communication actually started with the considering wavelength.

This type of laser 850 nanometre that is why 850 nanometre wavelength is considered the first generation communication window. However, later on it has been shifted as you go for longer wavelengths, we can find that fibre optics actually giving better properties. So, also people demonstrate it semiconductor laser diode emitting longer wavelengths, which is actually compatible to fibre, optical fibre, low loss optical fibre etcetera.

So, that is what we can discuss in a couple of slides and then we can close this lecture today. So, here actually you can see that this is when it is waveguide we can say that inside the waveguide how we can accommodate gain medium because, so, far we have discussed that in a waveguide is a passive waveguide whenever you are having a refractive in the high refractive index and then you can have a total internal reflection you can have a mode analysis orthogonality condition etcetera.

And you can guide your light and you can interfere them so and so on. But if there is a gain if it is lost you can consider it to be our - alpha that is the loss that coming from sigma and so on conductivity etcetera, but if there is a gain population inversion is there in that case also we can modify our dielectric constant like this it can have it can have real part of dielectric constant imaginary part of dielectric constant.

That means, your effective index of the guided mode can see the real part and imaginary part with g by 2 if you just replace your E to the power this beta, beta means 2 pi lambda times n effective. So, this n effective if it is real part and imaginary part that imaginary part normally in the effective index can give you your net gain as well as loss that is how we can represent I think this is easy to understand.

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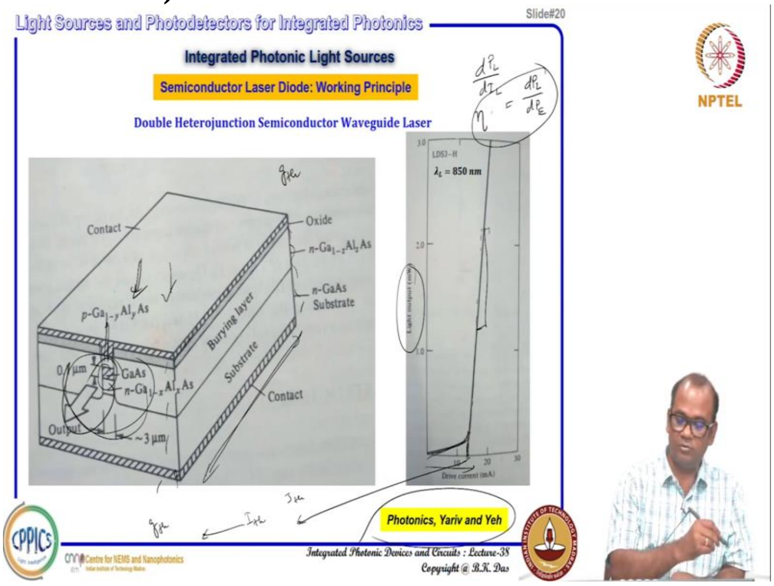

Light Sources and Photodetectors for Integrated Photonics

Slide#20

Integrated Photonic Light Sources

Semiconductor Laser Diode: Working Principle

Double Heterojunction Semiconductor Waveguide Laser

Photonics, Yariv and Yeh

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And here is one thing I mentioned that you are just giving this type of device here it is kind of 2 dimensional confinement waveguide you see this is the active region gallium arsenide all around you have an gallium arsenide and top side it is P type doping and this all around you can see N type doping and if you give a biasing here contact from here. So, there is some kind of insulating layer is there and then you can have a bias you can have a contact and bottom contact.

And you can h current and then light will be flowing this direction and this direction and forth, this is your mirror side here this side will be mirror side and then as I mentioned that you need at least a g threshold to overcome the loss inside mirror loss waveguide loss etcetera. So that you can get a laser emission, so that is that is the reason characteristics if you see initially as you increase your drive current.

Initially nothing happens very slowly some photons will be generated, but that is that will not be called as a laser because that is somehow some scattered photons coming out you can measure there, but after certain level you see that your emission light emission is hardly increasing almost linearly. So, that is actually laser and if you just normally you just consider as extra pole this one.

Where it is cutting that is actually called as a i threshold. i threshold if you divided by area then this will be called j threshold and this is i threshold actually is corresponding to the gain per unit length gain coefficient whatever you are getting threshold gain coefficient and you can find out and also you can see that this is called actually threshold gain. So, from here we can say that to get a laser at least your currents would be more than 10 million ampere 15 million ampere over here.

Now, if you just take a slope here, this one that means this is a light output say d P laser output by dI L that actually instead of I L you can think of how much electrical power you are actually consuming, you can consider something like that dP L laser power dP electrical power that will be called as a laser efficiency how much electrical power you are actually consuming and how much light power you are converting particularly you know that a laser is actually coming out by electrical currents.

So, driving electrical current in semiconductor you are getting laser light. So, that is actually we can define efficiency. So, you have to if you can eta = 1 that is actually you are not really losing anything whatever power electrical power you are consuming the same amount of light power we are getting, that is called laser efficiency. If you want to learn a little more about all these you can study the famous book photonics for optical communications written by Yariv and Yeh and you can get more insides on that.

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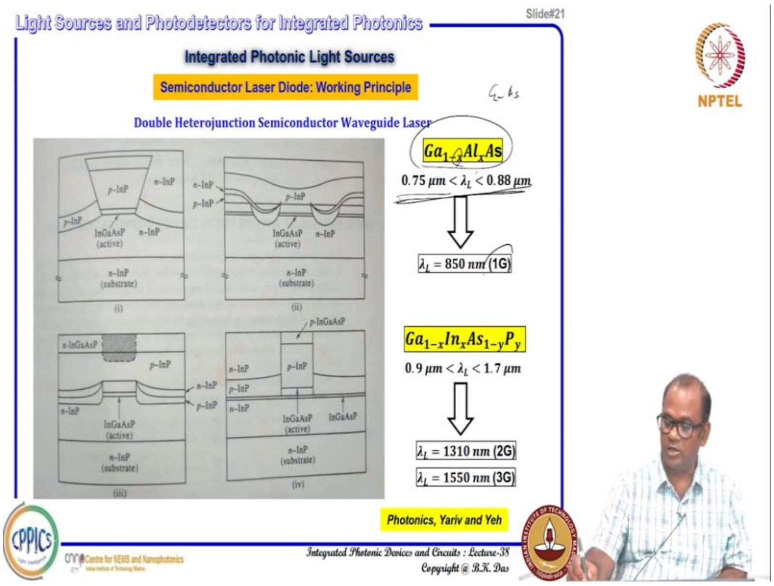

Light Sources and Photodetectors for Integrated Photonics

Integrated Photonic Light Sources

Semiconductor Laser Diode: Working Principle

Ga As

Double Heterojunction Semiconductor Waveguide Laser

$Ga_{1-x}Al_xAs$

$0.75\ \mu m < \lambda_L < 0.88\ \mu m$

$\lambda_L = 850\ nm$ (1G)

$Ga_{1-x}In_xAs_{1-y}P_y$

$0.9\ \mu m < \lambda_L < 1.7\ \mu m$

$\lambda_L = 1310\ nm$ (2G)

$\lambda_L = 1550\ nm$ (3G)

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And one I just want to complete one more thing. So, far we are talking about the first generation communication window because gallium arsenide lasers actually emits at 850 nanometre, but, as I mentioned that I will be also showing in the next lecture that if you just engineer if you just make some alloy composition suitably then you can actually also manufacture semiconductors compound semiconductor which can emits.

If you fabricate laser diode of course, it can emit longer wavelength also for example, gallium aluminium arsenide if you are just making then the bandgap you are just can control 0.75 micrometre 0.8 micrometre by controlling x here can x = 0 means it is basically gallium arsenide x = 0 means gallium arsenide, gallium arsenide. Now, keep on x increasing that means aluminium you are incorporating.

That means bandgap will keep on encouraging, encouraging and laser wavelength if you want to use that as the active element. So, you can control the wavelength from 750 nanometres to 818 nanometre. But normally using this thing I have shown there that 850 nanometre first generation communication window.