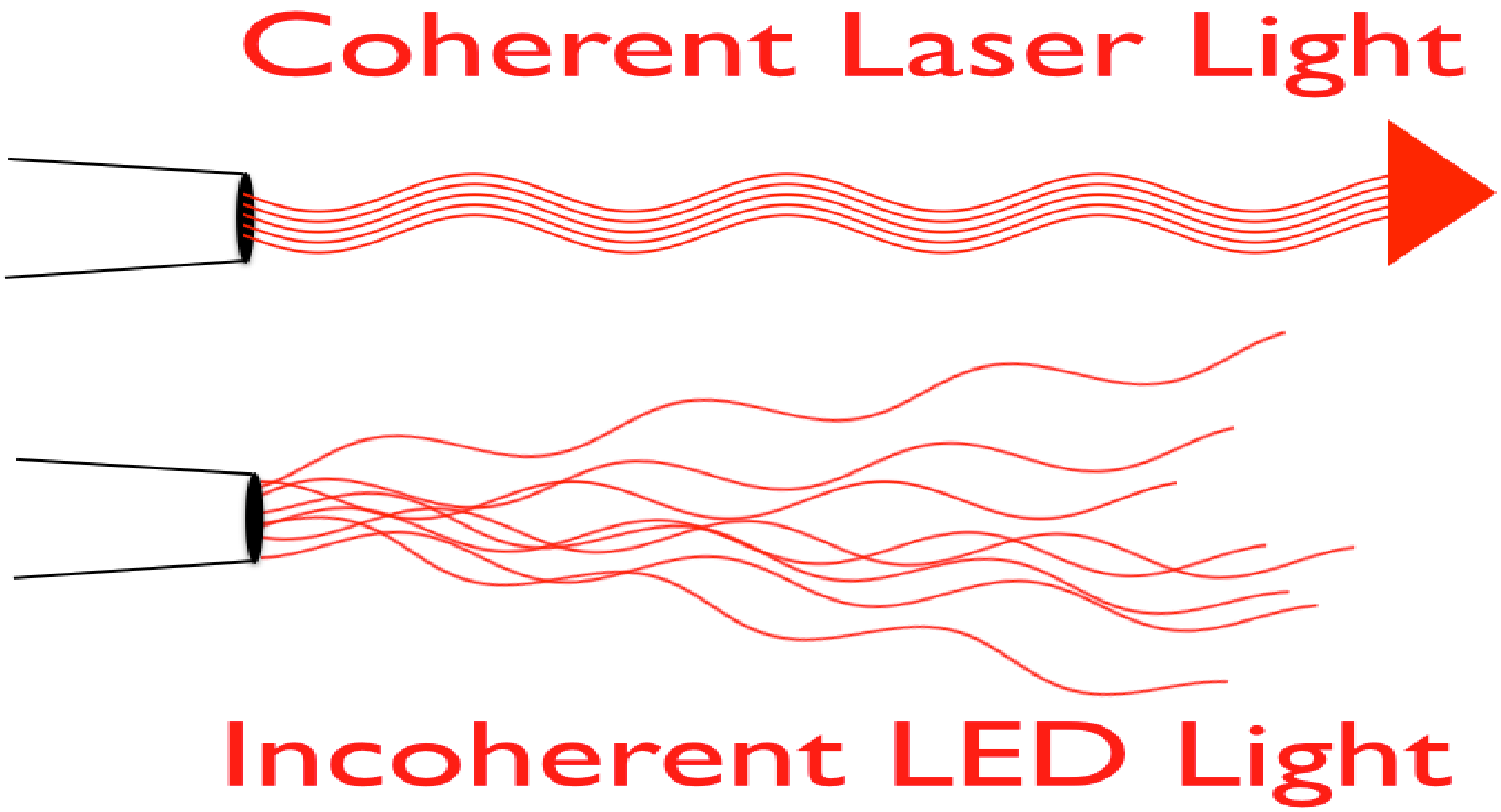

Module – 3
Optical Transmitters

Quantum Efficiency

- When there is no external carrier injection, the excess density decays exponentially due to electron-hole recombination

$$n(t) = n_0 e^{-t/\tau}$$

- n is the excess carrier density, n_o is the initial injected excess electron density, τ is the carrier lifetime.

- Bulk recombination rate R is

$$R = -\frac{dn}{dt} = \frac{n}{\tau}$$

- Bulk recombination rate (R) = Radiative recombination rate + non-radiative recombination rate.

Quantum Efficiency

- With an external supplied current density of J, the rate equation for the electron-hole recombination is:

$$\frac{dn(t)}{dt} = \frac{J}{qd} - \frac{n}{\tau}$$

- q is the charge of the electron, d is the thickness of recombination region

- In equilibrium condition: dn/dt=0

$$n = \frac{J\tau}{qd}$$

Internal Quantum Efficiency

- The internal quantum efficiency η_{int} of a semiconductor material is the ratio of the radiative electron-hole recombination coefficient to the total (radiative and nonradiative) recombination coefficient

- This parameter is significant because it determines the efficiency of light generation in a semiconductor material.

$$\eta_{\text{int}} = \frac{R_r}{R_r + R_{nr}} = \frac{\tau_{nr}}{\tau_r + \tau_{nr}} = \frac{\tau}{\tau_r}$$

- Bulk recombination life time τ is

$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$$

- Semiconductor optical sources require η_{int} to be large (in typical direct bandgap materials $\tau_r \approx \tau_{nr}$).

Order of magnitude values for recombination coefficients and lifetimes

material	r_r ($cm^3\ s^{-1}$)	τ_r	τ_{nr}	τ	η_{int}
Si	10^{-15}	10 ms	100 ns	100 ns	10^{-5}
GaAs	10^{-10}	100 ns	100 ns	50 ns	0.5

- The radiative lifetime for bulk Si is orders of magnitude longer than its overall lifetime because of its indirect bandgap. This results in a small internal quantum efficiency.
- For GaAs, the radiative transitions are sufficiently fast because of its direct bandgap, and the internal quantum efficiency is large.

Optical power

- If the current injected into the LED is I, then the total number of recombinations per second is

$$R_r + R_{nr} = \frac{I}{q}$$

$$R_r = \eta_{\text{int}} \frac{I}{q}$$

- Optical power generated internally in the active region in the LED is

$$P_{\text{int}} = R_r h\nu = \eta_{\text{int}} \frac{I}{q} h\nu = \eta_{\text{int}} \frac{hcI}{q\lambda}$$

Numerical problem

- The radiative and non-radiative recombination lifetimes of the minority carriers in the AR of the DH LED 60 ns and 100 ns respectively. Determine the total carrier recombination lifetime and the power internally generated within the device when the peak emission wavelength is 0.87 μm at a drive current of 40 mA.

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$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}} \qquad \tau = \frac{\tau_r \tau_{nr}}{\tau_r + \tau_{nr}} = 37.5ns$$

$$\eta_{\text{int}} = \frac{\tau}{\tau_r} = 0.625$$

$$P_{\text{int}} = \eta_{\text{int}} \frac{hcI}{q\lambda} = 35.6mW$$

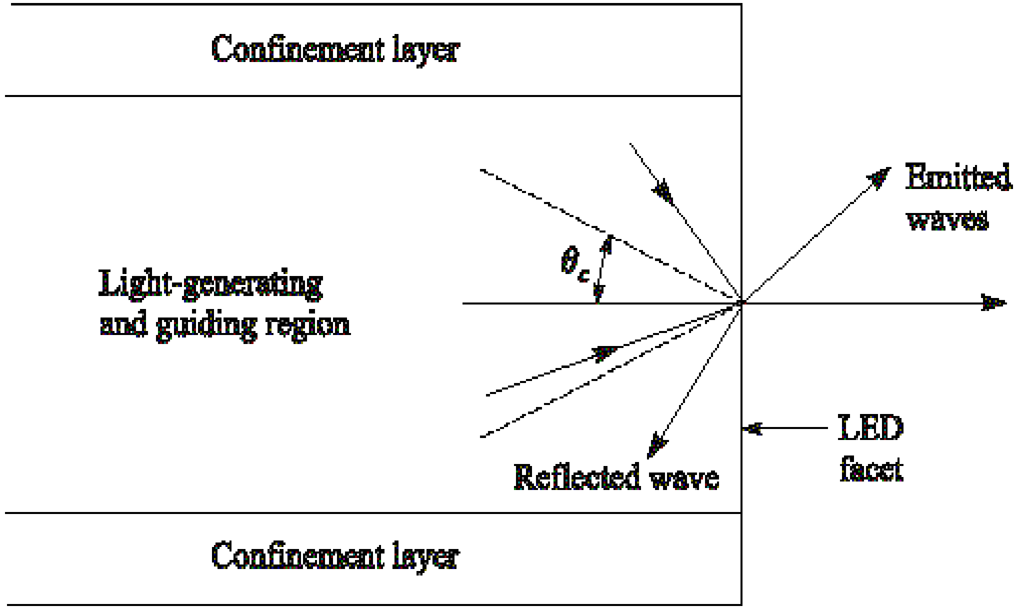
External Quantum Efficiency

$$\eta_{\text{ext}} = \frac{\text{number of photons emitted from LED}}{\text{number of internally generated photons}}$$

- In order to calculate the external quantum efficiency, we need to consider the reflection effects at the surface of the LED.

- If we consider the LED structure as a simple 2D slab waveguide, only light falling within a cone defined by critical angle will be emitted from an LED.

External Quantum Efficiency



$$\eta_{\text{ext}} = \frac{1}{4\pi}\int_0^{\phi_c} T(\phi)(2\pi \sin\phi)\,d\phi$$

$$T(\phi): \text{Fresnel Transmission Coefficient} \approx T(0) = \frac{4n_1 n_2}{(n_1+n_2)^2}$$

$$\text{If } n_2 = 1(air), n_1 = n \Rightarrow \eta_{\text{ext}} \approx \frac{1}{n(n+1)^2}$$

$$\text{LED emitted optical power, } P_{rad} = \eta_{\text{ext}} P_{\text{int}} \approx \frac{P_{\text{int}}}{n(n+1)^2}$$

Numerical problem

- An optical transmitter uses DH structure InGaAsP LED operating at a wavelength of 1550 nm and radiative & non-radiative recombination lifetimes of 25 ns & 90 ns respectively. If the LED is driven with a current of 35 mA,

(a). Find internal quantum efficiency and internal power.

(b). If n=3.5, then calculate the output emitted power.

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(b). If n=3.5, then calculate the output emitted power.

$$\tau = \frac{\tau_r \tau_{nr}}{\tau_r + \tau_{nr}} = 19.56ns$$

$$\eta_{\text{int}} = \frac{\tau}{\tau_r} = 0.7824$$

$$P_{\text{int}} = \eta_{\text{int}} \frac{hcI}{q\lambda} = 21.94mW$$

$$\eta_{\text{ext}} = \frac{1}{n(n+1)^2} = 0.0141$$

$$P_{rad} = \eta_{\text{ext}} P_{\text{int}} = \frac{P_{\text{int}}}{n(n+1)^2} = 0.309mW$$

Modulation of LED

- The frequency response of an LED depends on:
  - Doping level in the active region
  - Injected carrier lifetime in the recombination region, .
  - Parasitic capacitance of the LED

- If the drive current of an LED is modulated at a frequency of ω, the output optical power of the device will vary as:

$$P(\omega) = \frac{P_0}{\sqrt{1+(\omega\tau_i)^2}}$$

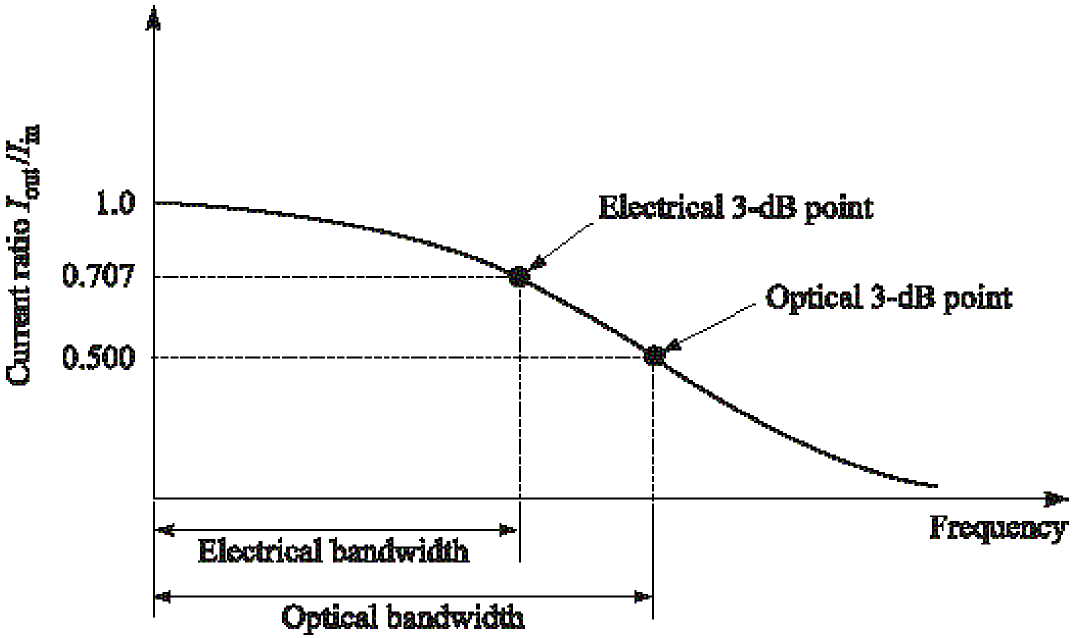
Modulation of LED

- Electrical current is directly proportional to the optical power, thus we can define electrical bandwidth and optical bandwidth, separately.

$$\text{Electrical BW} = 10\log\left[\frac{p(\omega)}{p(0)}\right] = 20\log\left[\frac{I(\omega)}{I(0)}\right] = \frac{1}{2\pi\tau_i}$$

p : electrical power, I : electrical current

$$\text{Optical BW} = 10\log\left[\frac{P(\omega)}{P(0)}\right] = 10\log\left[\frac{I(\omega)}{I(0)}\right] = \frac{\sqrt{3}}{2\pi\tau_i}$$



Numerical problem

- The minority carrier recombination lifetime for an LED is 5 ns. When a constant dc drive current is applied to the device, the optical output power is 300 uW. Determine the optical output power when the device is modulated with an rms drive current corresponding to the dc drive current at frequencies of (a) 20 MHz and (b) 100 MHz. Further determine the 3 dB optical bandwidth of the device and estimate the 3 dB electrical bandwidth assuming a Gaussian response.

Numerical problem

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$$P(20MHz) = \frac{P_0}{\sqrt{1+(\omega\tau_i)^2}} = 254.2\mu W \qquad P(100MHz) = \frac{P_0}{\sqrt{1+(\omega\tau_i)^2}} = 90.9\mu W$$

$$\text{Optical BW} = = \frac{\sqrt{3}}{2\pi\tau_i} = 55.1MHz \qquad \text{Electrical BW} = \frac{\text{Optical BW}}{\sqrt{2}} = 39.0MHz$$