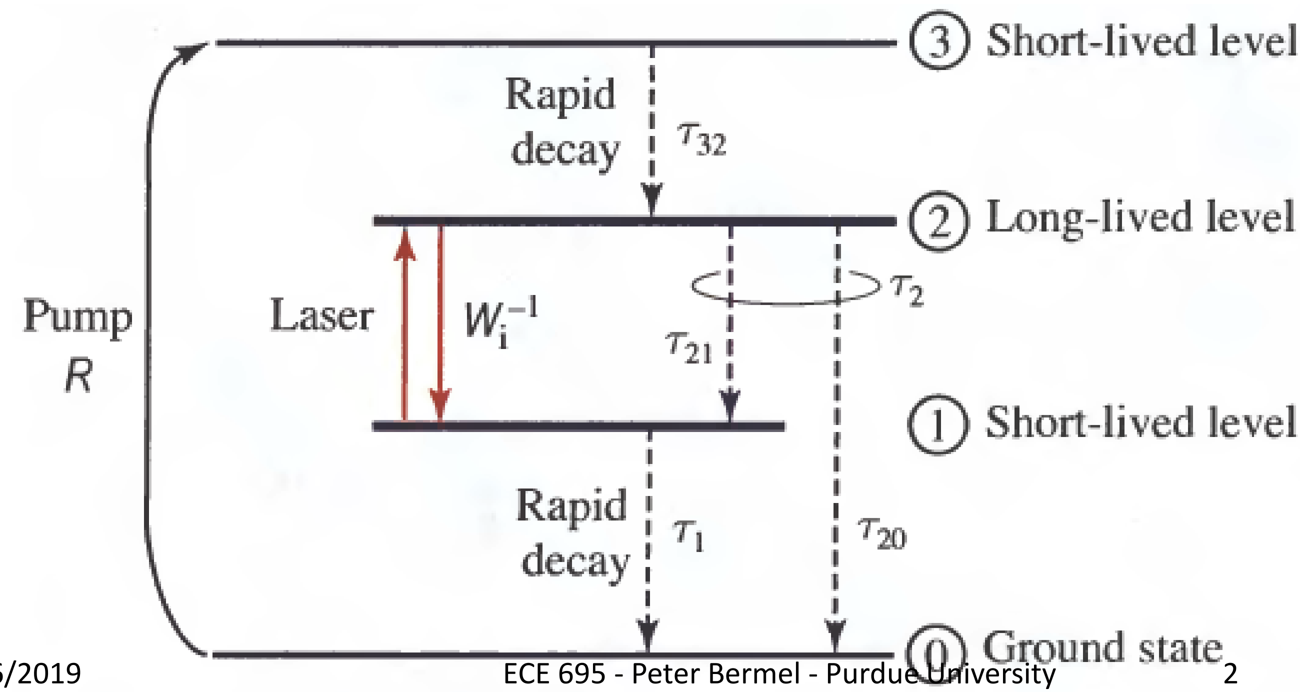
Fiber Optic Communications
Lecture 5: Semiconductor Lasers

- Amplification
- Lasing Conditions

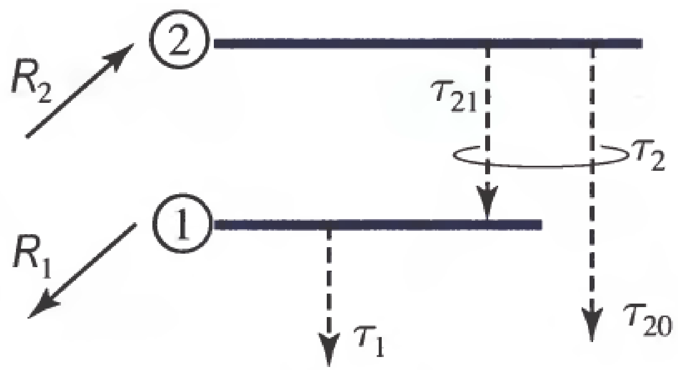
Four Level Pumping

- Population inversion is established between levels 2 and 1
- Level 2 is pumped through level 3 indirectly
- All four levels are involved, but the optical interaction of interest takes place between levels 2 and 1



Reduced four level system

- If decay from level 3 to 2 is very rapid, $R_2 = R$, the system is the same as the two-level system shown in the last lecture.
- Rates of change in population densities arising from pumping and decay:



$$\frac{dN_2}{dt} = R_2 - \frac{N_2}{\tau_2} \qquad \frac{dN_1}{dt} = -R_1 - \frac{N_1}{\tau_1} + \frac{N_2}{\tau_{21}}$$

Under Steady-State conditions, these equations can be solved, and the population difference can be determined

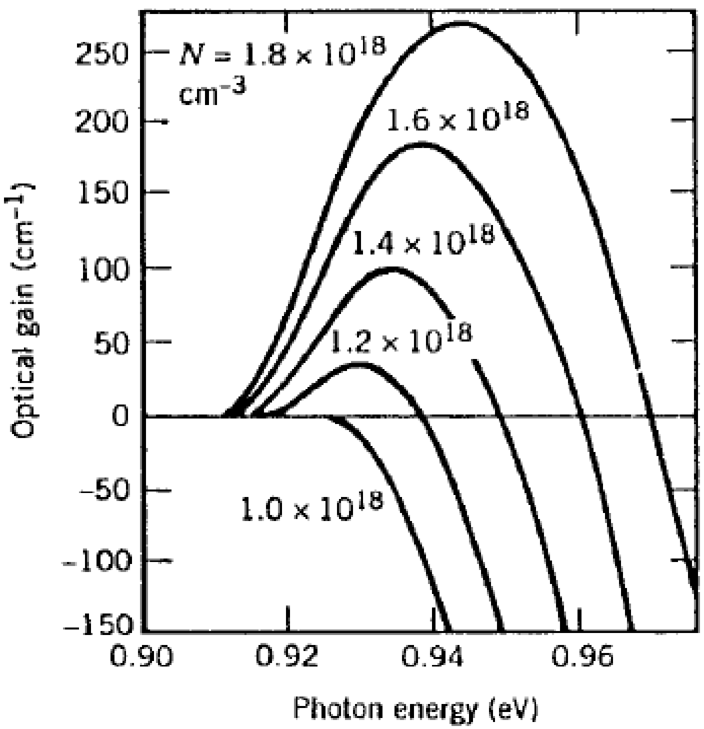
$$N_0 = R_2\tau_2\left(1 - \frac{\tau_1}{\tau_{21}}\right) + R_1\tau_1 \,,$$

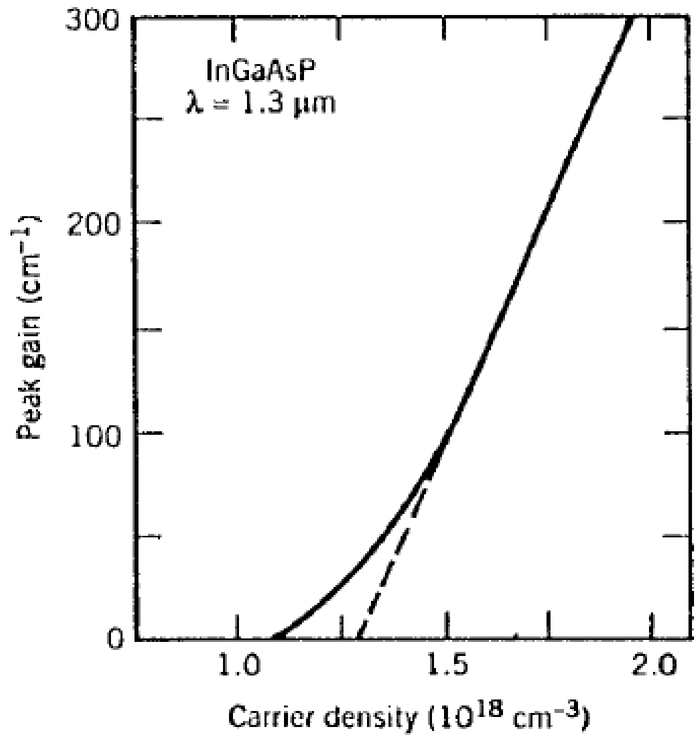
$R_1 = 0$ →

$$N_0 = R\tau_2\left(1 - \frac{\tau_1}{\tau_{21}}\right)$$

Amplification in Semiconductors

- Semiconductor gains depend on both joint density of electronic states and occupancy of states, as discussed last time
- Gain in semiconductors generally linear in pump rate, and population inversion, and thus given by $g_p(N) = \sigma_g(N - N_T)$





Amplification Saturation

- As the photon flux density increases, the amplifier saturates and its gain decreases.
- For Homogeneous broadening:

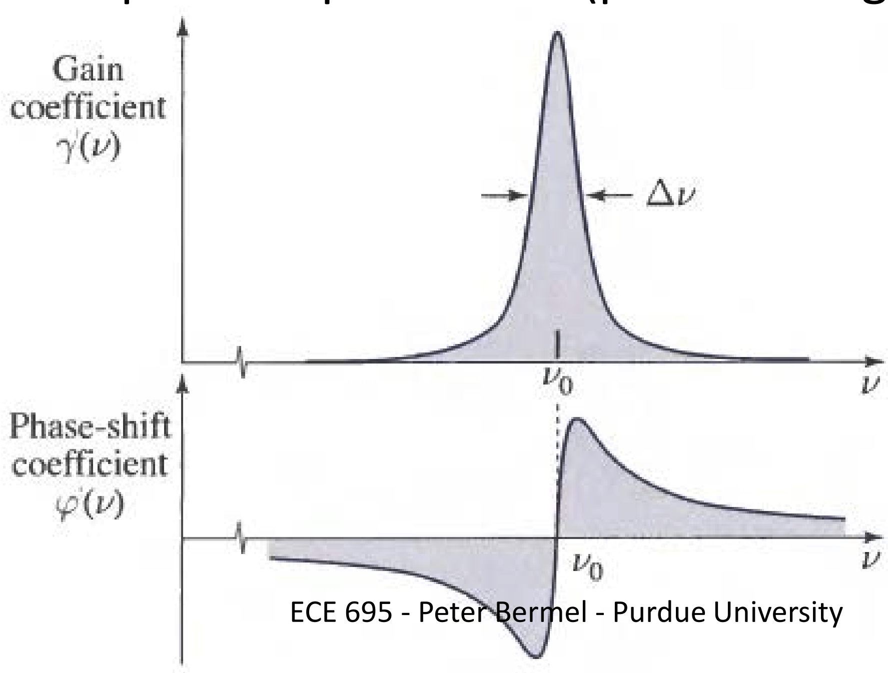
$$\gamma(\nu) = \frac{\gamma_0(\nu)}{1 + \phi/\phi_s(\nu)}.$$

$\phi_s(\nu) = [\tau_s\,\sigma(\nu)]^{-1}$ = saturation photon-flux density

τ_s = saturation time constant, which depends on the decay times of the energy levels involved; in an ideal four-level pumping scheme, $\tau_s \approx t_{sp}$, whereas in an ideal three-level pumping scheme, $\tau_s = 2t_{sp}$

- The laser's lineshape has a phase shift (per unit length):

$$\varphi(\nu) = \frac{\nu - \nu_0}{\Delta\nu}\,\gamma(\nu).$$



Feedback and Loss: Optical Resonator

- Feedback is achieved by placing the active medium in an optical resonator
- Travelling through the medium produces a phase shift of:

$$k = \frac{2\pi\nu}{c}.$$

- Absorption and scattering in the resonator introduce loss: $\exp(-2\alpha_r d) = \mathcal{R}_1\mathcal{R}_2 \exp(-2\alpha_s d)$

Distributed loss coefficient (total energy lost) → $\alpha_r = \alpha_s + \alpha_{m1} + \alpha_{m2}$

Loss contributions of mirrors:

$$\alpha_{m1} = \frac{1}{2d} \ln\frac{1}{\mathcal{R}_1}$$

$$\alpha_{m2} = \frac{1}{2d} \ln\frac{1}{\mathcal{R}_2},$$

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Conditions for Laser Oscillation

- Two conditions must be satisfied for the laser to lase
- The gain condition determines the minimum population difference, and the pumping threshold required for lasing
- The phase condition determines the frequencies at which oscillations take place

Gain Condition: Laser Threshold

- The gain coefficient must be larger than loss coefficient

$$\gamma_0(\nu) > \alpha_r,$$

- $N_0 > N_t$ where N_t is the Threshold Population Difference:

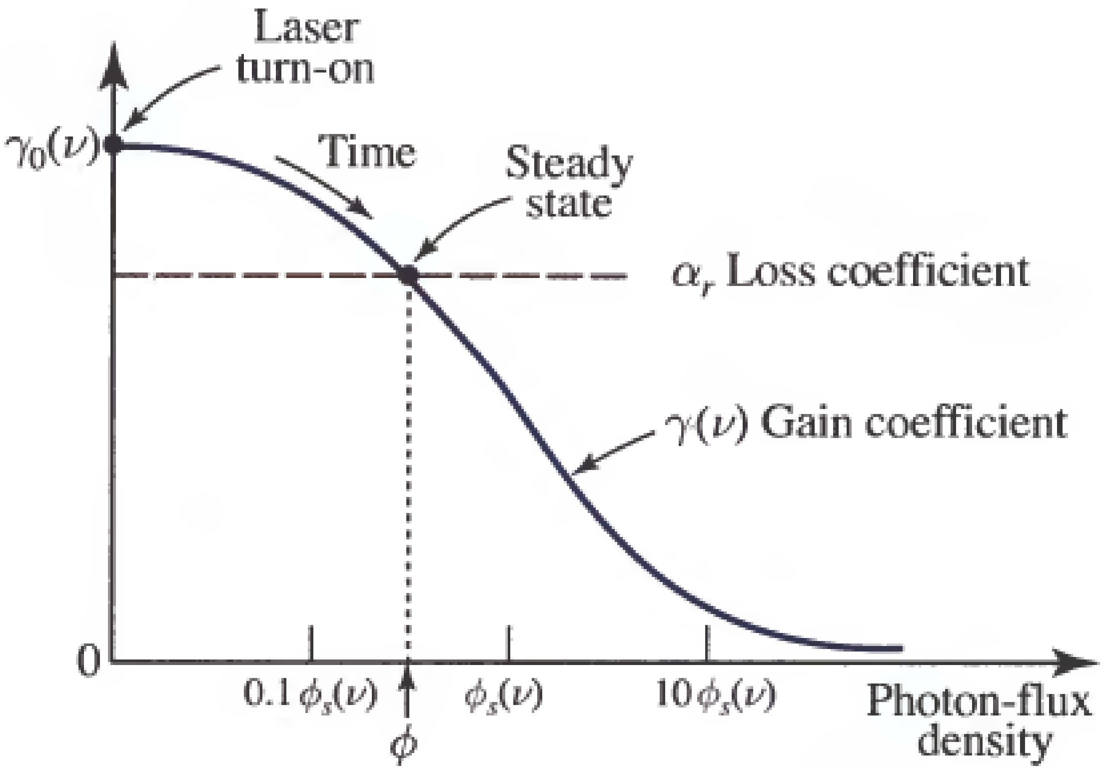
$$N_t = \frac{\alpha_r}{\sigma(\nu)} = \frac{8\pi}{\lambda^2 c}\frac{t_{sp}}{\tau_p}\frac{1}{g(\nu)} = \frac{2\pi}{\lambda^2 c}\frac{2\pi\Delta\nu\, t_{sp}}{\tau_p} = \frac{2\pi}{\lambda^2 c\tau_p} = \frac{2\pi\alpha_r}{\lambda^2}$$

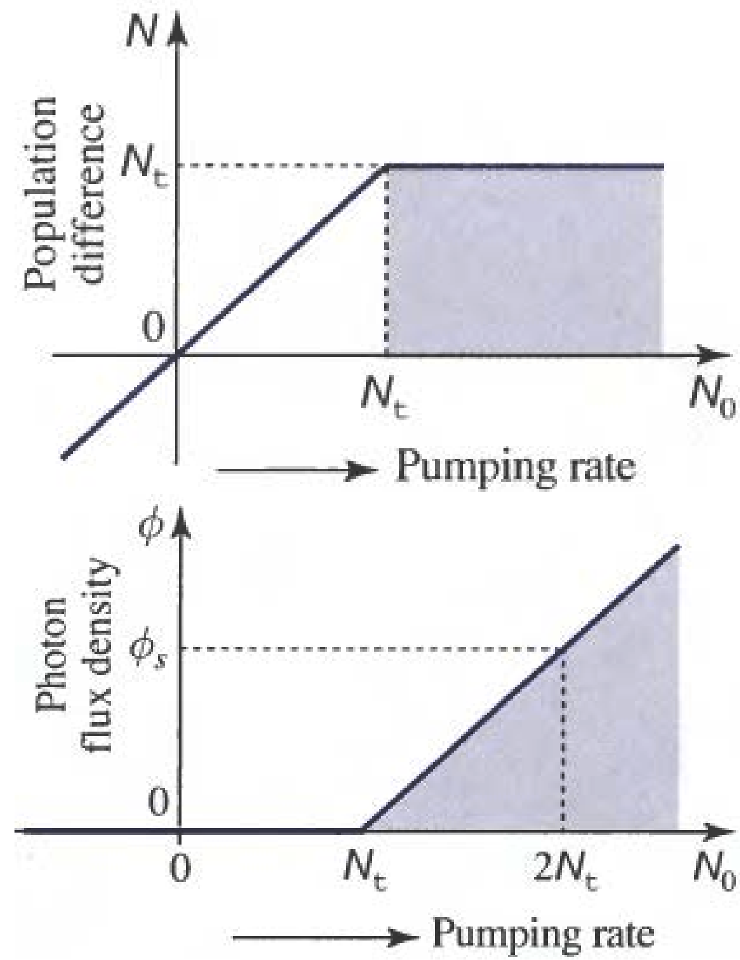
Phase Condition: Laser Frequencies

- The phase shift imparted to a light wave completing a round trip within the resonator must be a multiple of 2π:

$$2kd + 2\varphi(\nu)d = 2\pi q, \qquad q = 1, 2, \ldots .$$

Internal Photon-Flux Density





$$\phi = \begin{cases} \phi_s(\nu)\left(\dfrac{N_0}{N_t} - 1\right), & N_0 > N_t \\ 0, & N_0 \le N_t . \end{cases}$$

Optimize Output Photon-Flux Density

- Only a portion of the steady-state internal photon flux density leaves the resonator as useful light
- It is useful to optimize the amount of light leaving the oscillator

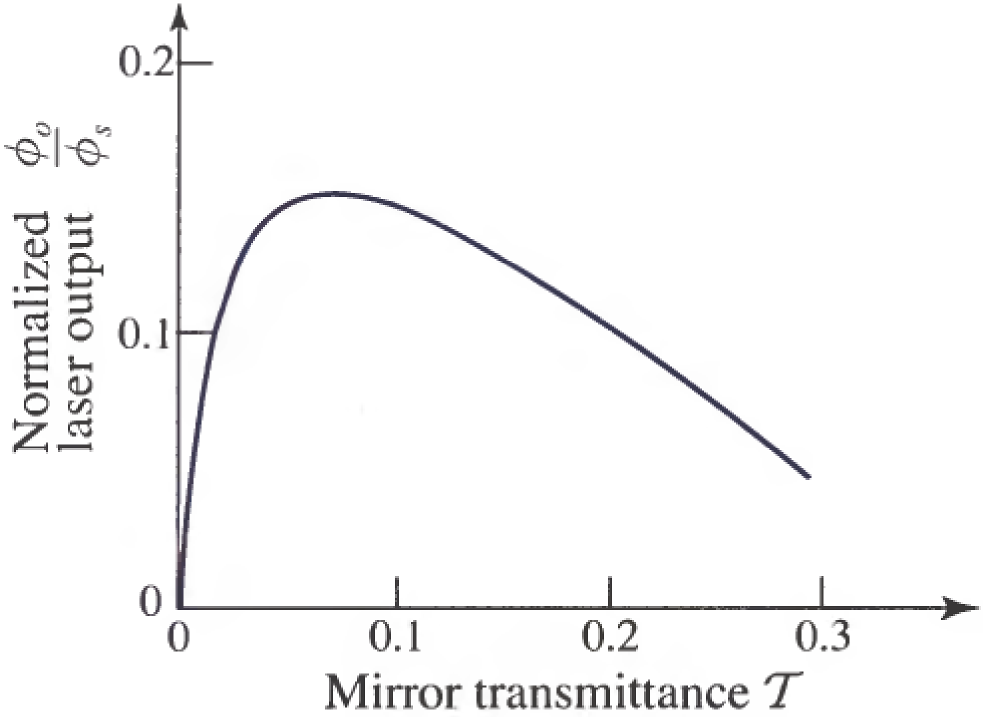
$$\mathcal{T}_{\text{op}} \approx \sqrt{g_0 L} - L$$

$$g_0 = 2\gamma_0(\nu)d\,, \quad L = 2(\alpha_s + \alpha_{m2})d$$

Internal Photon-Number Density

- The steady-state number of photons per unit volume in a resonator is:

$$n = \frac{\phi}{c} .$$



$$n = n_s\left(\frac{N_0}{N_t} - 1\right), \qquad N_0 > N_t ,$$

$$n = (N_0 - N_t)\frac{\tau_p}{\tau_s}, \qquad N_0 > N_t .$$

Output Photon Flux and Efficiency

- If there are losses other than the output laser mirror, the output flux can be written as:

$$\Phi_o = \eta_e (R - R_t) V$$

- η_e is the extraction efficiency, which is the ratio of the loss arising from the extracted useful light to all of the total losses in the resonator

$$\eta_e \approx \frac{\tau_p}{T_F} \mathcal{T},$$

$$1/T_F = c/2d$$

$$\eta_c = \frac{P_o}{P_p}.$$

P_O = output optical power
P_p = supplied pump power

$$\eta_s = \frac{dP_o}{dP_p}.$$

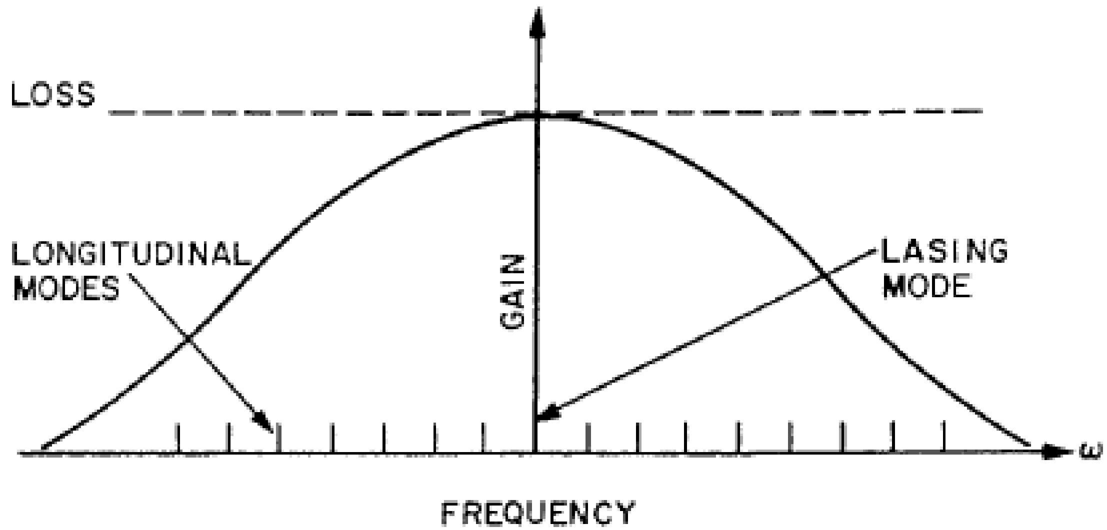
η_s is the slope efficiency

Spectral Distribution

- Two conditions for laser oscillations:

1. The gain condition requiring that the initial gain coefficient of the amplifier be greater than the loss coefficient [$\gamma_0(\nu) > \alpha_r$] is satisfied for all oscillation frequencies lying within a continuous spectral band of width B centered about the atomic resonance frequency ν_0, as illustrated in Fig. 15.2-4(a). The bandwidth B increases with the atomic linewidth $\Delta\nu$ and the ratio $\gamma_0(\nu_0)/\alpha_r$; the precise relation depends on the shape of the function $\gamma_0(\nu)$.
2. The phase condition requires that the oscillation frequency be one of the resonator modal frequencies ν_q (assuming, for simplicity, that mode pulling is negligible). The FWHM linewidth of each mode is $\delta\nu \approx \nu_F/\mathcal{F}$ [Fig. 15.2-4(b)].

Spectral Distribution



- Only a finite number of oscillation frequencies are *possible*. The number of possible laser oscillation modes is therefore:

$$M \approx \frac{B}{\nu_F},$$

Where ν_f = c/2d is the spacing between adjacent modes