6. Theory of Experiments

1) Basic structure of a semiconductor laser

The gain media employed by semiconductor lasers are GaAs or $Ga_{1-x}Al_xAs$ materials with a *p-n* junction, a *p*-layer is grown on top of an *n*-layer, shown in Figure 1. Ohmic contact is prepared for both *p*- and *n*-regions so that an excitation electric current can flow across the *p-n* junction for the realization of population inversion of electrons in the *p-n* junction. In addition, the side ends of the semiconductor device should be mirror polished acting as the resonance cavity. The device shown in Figure 1 is discrete, but it can be optically coupled into an optical fiber or designed with a multi-layer structure to provide complicated functions of optical feedback to form a highly integrated opto-electronic device.

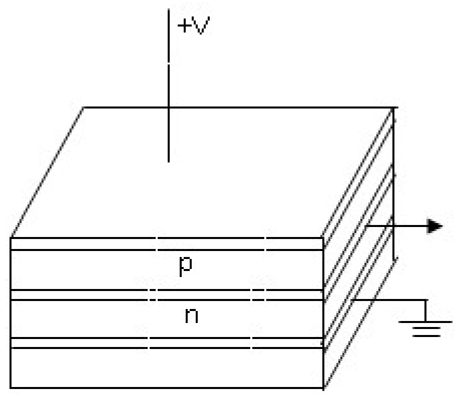

Figure 1 Structure of semiconductor laser

2) Threshold condition of semiconductor laser

When a forward bias is applied to the *p-n* junction as seen in Figure 1, no laser oscillation would occur within the device. Light emission under small current excitation comes from spontaneous emission with spectral linewidth on the order of a few hundred Angstroms. With an increase in excitation current, population inversion increases across the *p-n* junction and more photons are emitted. When the excitation current exceeds the threshold current, transition from spontaneous emission to stimulated emission occurs. Such sudden transition can be observed by monitoring the change of output laser power with respect to the excitation current, as shown in Figure 2. This results from the higher quantum efficiency under stimulated emission.

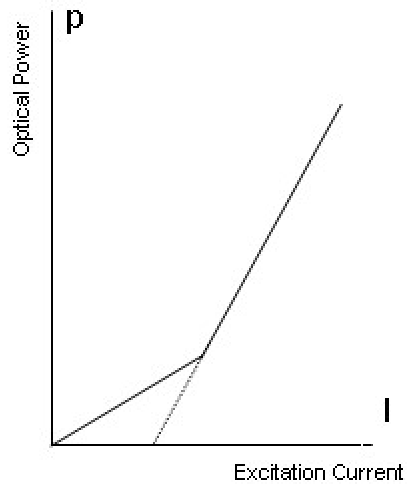

Figure 2 Output power curve of a semiconductor laser vs excitation current

Quantitatively, the lasing threshold of a semiconductor laser corresponds to a condition under which the number of stimulated photons per unit time is equal to the total number of photons lost per unit time due to optical scattering and absorption losses within the laser. Thus, the threshold current of a semiconductor laser can be expressed as

$$J_{th} = \frac{8\pi e n^2 \Delta\gamma D}{\eta_Q \lambda_0^2}\left[a + \frac{1}{2L}\ln\left(\frac{1}{R}\right)\right] \tag{1}$$

where η_Q is the internal quantum efficiency, λ_0 is the wavelength of emitted light in vacuum, n is the refractive index of the gain medium, $\Delta\gamma$ is the linewidth of spontaneous emission, e is the electric charge of an electron, D is the thickness of light emissive layer, a is the loss efficient of traveling wave, L is the cavity length, and R is the reflectivity of cavity mirrors.

3) Transverse mode and polarization state

The resonant cavity of a semiconductor is a dielectric waveguide so that light propagation in the cavity is represented by modes. Each mode is associated with its own propagation constant β_m and the transverse distribution of the electric field. These modes are called the transverse modes of a semiconductor laser and the output of a transverse mode from the resonant cavity forms a radiation field. The angular distributions of such radiation field parallel with and perpendicular to the end surface of the cavity are called side-view transverse field and front-view transverse field, respectively. The angular distribution of a radiation field depends on the geometrical size of the resonant cavity. The smaller transverse size of a resonant cavity, the larger divergent angle distribution of its radiation field will be. Because the width of the resonant cavity parallel to the end surface of the cavity is larger than the thickness of the cavity perpendicular to the end surface of the cavity, the divergent angle of the side-view transverse field is smaller than that of the front-view transverse field, as shown in Figure 3.

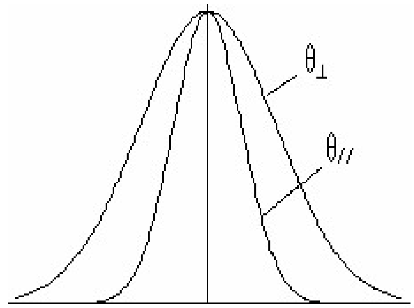

Figure 3 Divergent angles of side-view and front-view transverse fields

The divergent angle of a side-view transverse field can be approximated as

$$\theta_{//} = \frac{\lambda}{d} \tag{2}$$

where d is the width of a resonant cavity while the thickness of a resonant cavity is normally around 1 μm on the same order of the laser wavelength. Hence, the divergent angle of a front-view transverse field is larger, usually around 30° to 40°. In addition, the divergent angle of a radiation field is inversely proportional to the length of the resonant cavity. Because the length of a semiconductor laser cavity is only a few hundred microns, much shorter than those of gas or solid-state lasers, the far-field divergent angle of semiconductor lasers is much larger than those of gas or solid-state lasers.

The surfaces of the resonant cavity of a semiconductor laser are normally the cleavage planes of the semiconductor crystal. For a common GaAs hetero junction laser, the surface reflectivity of the GaAs crystal is larger to a TE mode than a TM mode. Hence, the threshold gain required by a TE mode is lower and therefore stimulated emission occurs to a TE mode firstly. This in turn suppresses the stimulated emission of a TM mode. On the other hand, the thickness of the waveguide layer of a semiconductor laser cavity is so thin that it highly absorbs TM modes with polarization perpendicular to the waveguide layer. These factors further enhance the gain of TE modes for stimulated emission. Thus, semiconductor lasers are highly polarized. The degree of polarization of a semiconductor laser can be calculated as

$$p = \frac{I_{//} - I_{\perp}}{I_{//} - I_{\perp}} > 90\% \tag{3}$$

where $I_{//}$ and $I_{\perp}$ are the laser intensities of TE and TM polarization, respectively.

4) Characteristics of longitudinal modes

The optical feedback from reflections by the end surfaces of a semiconductor laser cavity gives rise to a single or multiple longitudinal modes. Similar to the resonant cavity of a Fabry-Perot interferometer, the resonant cavity of a semiconductor laser is also called the Fabry-Perot cavity. When the spacing between the two end surfaces of a Fabry-Perot cavity is a half-integral number of the wavelength, standing waves are formed within the resonant cavity. The modal number, m, can be derived by

$$m = \frac{2nL}{\lambda_0} \tag{4}$$

where L is the cavity length, n is the refractive index of the gain medium, and λ_0 is the laser wavelength in vacuum. The wavelength spacing between two longitudinal modes is given by

$$\frac{dm}{d\lambda_0} = -\frac{2nL}{\lambda_0^2} + \frac{2L}{\lambda_0}\frac{dn}{d\lambda_0} \tag{5}$$

From equation (5), the wavelength spacing between adjacent longitudinal modes (dm=-1) is

$$d\lambda_0 = \frac{\lambda_0^2}{2L\left(n - \lambda_0 \dfrac{dn}{d\lambda_0}\right)} \tag{6}$$

The spectrum of a typical semiconductor laser is shown in Figure 4, in which there exist several longitudinal modes whose wavelengths are close to those of spontaneous emissions. The spacing between adjacent longitudinal modes of a GaAs laser is about 0.3 nm. To achieve a single-mode (longitudinal) laser, the structure of the laser must be improved to suppress all the modes other than the fundamental mode.

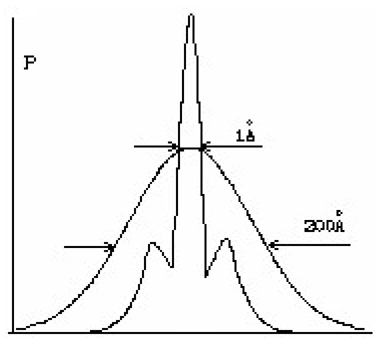

Figure 4 Spectrum of a typical semiconductor laser