2. Theory

A. Introduction to Semiconductor Laser

With the development of opto-electronic devices and technologies, semiconductor lasers have evolved rapidly in manufacturing and applications. Today, semiconductor lasers have been applied to optical communication and compact disk systems. Semiconductor lasers can also be used as the light source of high-resolution infrared spectrometers for monitoring atmospheric pollution and resolving isotopes. In general, semiconductor lasers can be used as the light source in a variety of applications such as radars, range finders, hologram recording and reconstruction, shooting simulators, infrared night-vision goggles, and alarms. The integration of semiconductor laser, modulator, and amplifier promotes the development of optical communication and optical computer.

Generally speaking, a laser is composed of three components.

1) Laser gain medium

A suitable gain medium, gas, liquid, solid, or semiconductor, is required for the creation of a laser. In the gain medium, population inversion of atoms or molecules is the necessary condition for lasing. Obviously, the existence of a metastable state benefits the realization of population inversion. So far, there are nearly a thousand gain media that can be used for laser creation from ultraviolet to far-infrared wavelength range.

2) Excitation source

To realize population inversion of atoms or molecules in a gain medium, the atoms or molecules in lower state must be excited to increase the population of atoms or molecules of upper states. A gas discharge lamp can be used to excite the atoms in a gain medium with the kinetic energy of electrons, called electric excitation; or a pulsed light source can be used to illuminate the gain medium, call optical excitation. Alternatively, there are thermal and chemical excitations. In general, all the excitation methods can be expresses by a technical term called “pumping”. To obtain a steady laser output, atoms must be continuously pumped from lower state to upper state to maintain a population inversion.

3) Resonant cavity

Upon the realization of population inversion of atoms in a gain medium, stimulated emission of light occurs. However, the intensity of such stimulated emission is weak without an optical amplifier-a resonant cavity. A resonant cavity is normally composed of two mirrors with high reflectivity, attached to either end of a gain medium. One mirror is totally reflective while the other mirror is highly reflective (slightly transmissive) so laser light can be transmitted through the second mirror. Stimulated emission is circulated within the cavity as reflected by the cavity mirrors, thus optical amplification of stimulated emission is realized, the realization of laser light.

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.

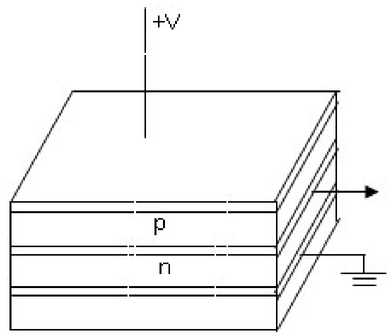

Figure 1 Structure of semiconductor laser

B. Common Parameters of Semiconductor Laser

The common parameters of semiconductor lasers include wavelength λ, threshold current I_{th}, operating current I_{op}, vertical divergence angle $\theta_{\perp}$, horizontal divergence angle $\theta_{//}$, and monitoring current I_m.

1) Wavelength λ: the working wavelength of the laser device. The wavelengths of semiconductor lasers currently available cover a wide optical spectral range from UV to far infrared.
2) Threshold current I_{th}: the current at which the laser device starts to emit laser. For a low-power laser device, its value is about tens of milli-amperes.
3) Working current I_{op}: the driving current when the laser tube reaches the rated output power. This value is important for the design and test of the laser driving circuit.
4) Vertical divergence angle $\theta_{\perp}$: the angle at which the luminous band of the laser diode spreads in the direction perpendicular to the PN junction and is generally around 15°-40°.
5) Horizontal divergence angle $\theta_{//}$: The angle at which the luminous band of the laser diode spreads in the direction parallel to the PN junction and is generally around 6°-10°.
6) Monitoring current I_m: the current flowing on the PIN device when the laser device is at rated output power.

C. Far Field Characteristics of Semiconductor Laser

The far-field characteristic refers to the spatial distribution of the light beam at a certain distance from the output cavity surface, and it is often related to the amount of the beam divergence angle. Due to the asymmetry of the cross-section of the active layer of the semiconductor laser and the thin active region, the output beam has a large divergence angle, and the light intensity distribution (spot shape) is also asymmetric. The divergence angle in the plane of perpendicular to the PN junction is larger than the divergence angle parallel to the PN junction plane, as shown in Figure 2:

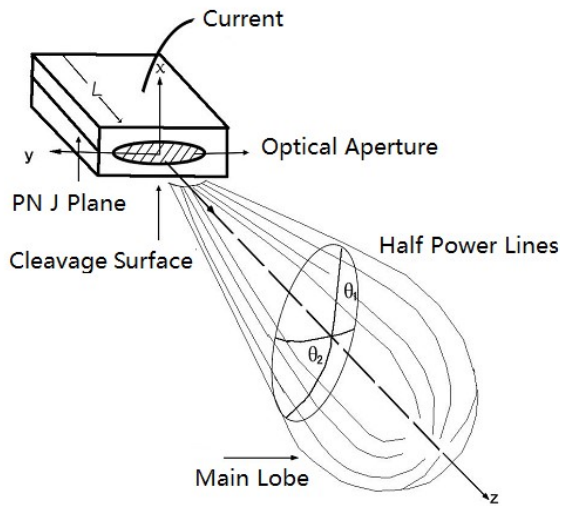

Figure 2 Far-field pattern of a semiconductor laser

The measurement methods of the far-field characteristics of semiconductor lasers are as follows:

1) Place the semiconductor laser in the center of the rotation stage.
2) Let the laser beam be parallel to the plane of the rotary table.
3) Remove the collimating lens of the laser head (note that there is a thin spring behind the collimating lens, and pay attention to keep it during the experiment).
4) Fix the distance between the probe of the laser power meter and the semiconductor laser.
5) Set the constant temperature control of the semiconductor laser (generally set at room temperature $30^{o}C$) and a constant output voltage (for example, 2.4 V).
6) Turn the rotary table to different angles, write down the readings of the laser power meter.
7) Plot the curve of the measured output power changing with the angle.
8) Rotate the semiconductor laser 90 ° and measure the horizontal divergence angle.
9) The full angular widths at the two half-power intensity points are respectively recorded as $\theta_{\perp}$ and $\theta_{//}$. Note: due to the limitation of the device conditions (e.g. the laser housing may partially block the vertical light), there is a certain deviation from the theoretical situation.

D. V-I Characteristics of Semiconductor Laser

Volt-ampere characteristics describe the purely electrical properties of semiconductor lasers, usually expressed by V-I characteristic curves, as shown in Figure 3. One parameter related to the V-I characteristic is the equivalent resistance (or series resistance) of the semiconductor laser. A derivative of the V-I curve can determine the equivalent resistance (dV / dI) at the operating current (*I*). It is always desirable for semiconductor lasers to have a small series resistance.

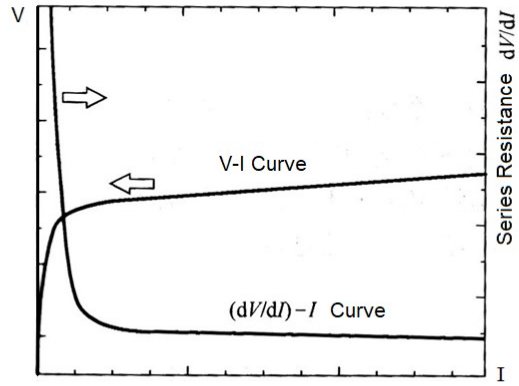

Figure 3 Typical V-I characteristic curve of semiconductor lasers

E. P-I Characteristics of Semiconductor Laser

The relationship between the output optical power (*P*) of the semiconductor laser and the driving current (*I*) is shown in Figure 4. This characteristic has a turning point, where the corresponding driving current is called the threshold current I_{th}. Below the threshold current, the laser operates at spontaneous emission and outputs fluorescence with very small power. Above the threshold current, the laser works in stimulated emission and outputs laser light. The optical power rises rapidly with the drive current, which is basically linear. The relationship between the current and voltage of the laser is similar to the characteristics of a forward diode. According to the P-I characteristic curve of the semiconductor laser, the threshold current I_{th} can be determined in this experiment.

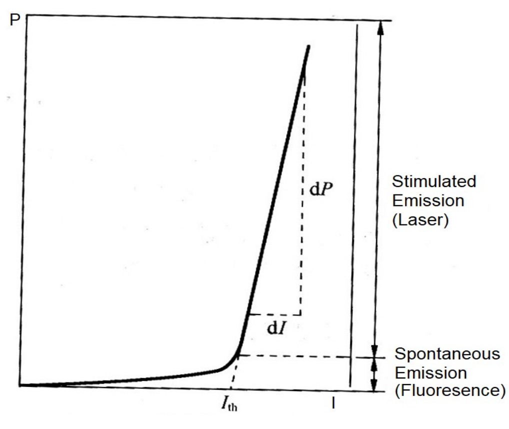

Figure 4 P-I characteristic curve of semiconductor laser

F. Temperature Characteristics of Semiconductor Laser

As the temperature rises, the threshold current increases exponentially, i.e. $I_{th}(T) = I_0 e^{T/T_0}$, the output power decreases significantly, and the laser does not lasing when it reaches a certain temperature. Figure 5 shows the changes of P-I curve with temperature.

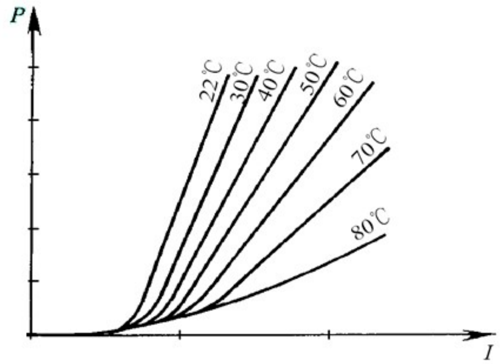

Figure 5 P-I curve changes with temperature

G. Polarization Characteristics of Semiconductor Laser

The light generated by the semiconductor laser is partially polarized light. The parameter that measures the degree of polarization is defined as $P' = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$. For linearly polarized light, $P' = 1$, for natural light, $P' = 0$, and for partially polarized light, $0 < P' < 1$.

According to the Malus's law, a linearly polarized light with intensity I_m passes through an analyzer, the intensity of the transmitted light is $I = I_0 \cos^2 \phi$, where ϕ is the angle between the polarization direction of the incident light and the polarization axis of the analyzer, and I_0 is the intensity of the transmitted light when the analyzer optical axis is parallel to the analyzer optical axis (since the analyzer has absorption and reflection, $I_0 < I_m$). Therefore, it is possible to distinguish between linearly polarized light, natural light, and partially polarized light according to the change in transmitted light intensity by rotating the polarization angle of the analyzer.