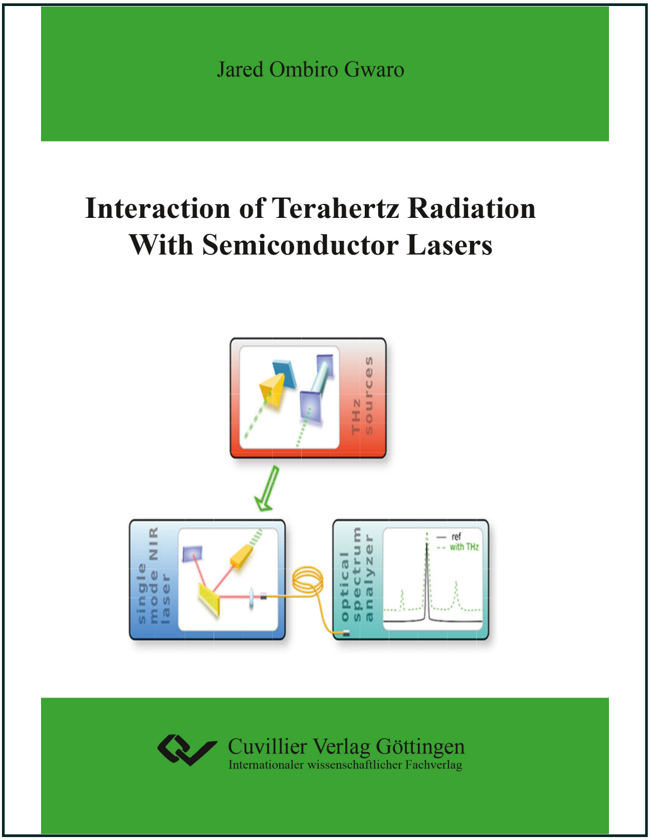
Jared Ombiro Gwaro (Autor)

Interaction of Terahertz Radiation with Semiconductor Lasers



Jared Ombiro Gwaro

Interaction of Terahertz Radiation
With Semiconductor Lasers

Cuvillier Verlag Göttingen
Internationaler wissenschaftlicher Fachverlag

https://cuvillier.de/de/shop/publications/8055

Copyright:
Cuvillier Verlag, Inhaberin Annette Jentzsch-Cuvillier, Nonnenstieg 8, 37075 Göttingen, Germany
Telefon: +49 (0)551 54724-0, E-Mail: info@cuvillier.de, Website: https://cuvillier.de

Chapter 1

Introduction

The terahertz (THz) spectral region (0.1-10 THz) remained unexplored part of the electromagnetic frequencies for quite sometime hence was commonly described as the forgotten gap or THz gap. This was mainly attributed to scarcity of excellent THz emitters and receivers in the THz spectral region. However, in the recent years, a lot of research attention has been witnessed in this spectral region leading to great research progress devoted to development of novel THz sources and detectors [1]. The advance in optoelectronic THz generation and detection techniques has led to an increased interest for THz applications in many existing and emerging fields such as medicine, security, manufacturing, basic sciences, and communications. Such great attention in the THz radiation and its potential applications has taken the THz research a notch higher with a lot of activities devoted towards development of cost effective and efficient THz emitters as well as THz detectors with high sensitivity [2].

Considerable approaches to detect THz radiation have been developed. This includes, detectors such as Schottky diode, photoconductive antenna and electro-optic detection and thermal detectors [3], [4]. Pyroelectric detectors, Bolometers and Golay cells are the conventional THz detectors, which belong to the class of thermal detectors and provides broadband spectral response, however they are large in size, and have slow sensitivity due to thermal detection mechanism of heating a material before detection is achieved and can only measure the intensity of THz radiation [4], [5]. In contrast, the photoconductive or electro-optic detection can provide direct access to temporal THz transients and thus provide both phase and amplitude of a THz wave which is desired information for high spectral resolution spectrocopy and imaging applications. But usually, this detection concept requires rather complex measurement schemes. So, in summary, the realization of efficient THz sources and detectors is still probably the most challenging part of THz technology.

In general, THz radiation can be categorised into two groups namely: pulsed THz source commonly referred as broadband and continuous wave (CW) THz sources also known as narrowband sources. Different mechanisms are involved in the generation of pulsed THz sources as well as CW THz sources. For pulsed systems for example, by exciting a semiconductor material with ultra-short laser pulses one can generate THz transient, by ultilizing nonlinear mixing processes in non-linear crystals or photoconductive antennas. The generation of THz transient with ultra-short pulse can provide a THz radiation with broad spectrum of THz frequencies. CW THz sources on the other hand can be generated with differnt means such as electric source, Gunn diodes, THz gas lasers, photomixers, difference frequency generation, quantum cascade lasers as well as free-electron lasers. CW THz emitters generates a THz wave signal with a narrower linewidth when compared to pulsed THz sources however with a higher spectral THz power. Unlike in pulsed system where power is distributed throughout the entire spectrum, in CW THz power is concentrated on a single frequency. CW THz sources are highly desired in high-resolution THz spectroscopy, imaging as well as in wireless communications [2].

THz spectroscopy requires usually THz radiation with wide frequency range which is tunable and has sufficient power levels in the range of microwatts. In addition, THz source having small size, low cost and room temperature operation condition will be highly suited for such application [3]. Some of the systems mentioned above can generate relatively high emission power. However, they are large in size, cost a fortune and their tunable frequency range is limited [6]. It is still technologically challenging to develop compact CW THz systems that can provide broad tunability of frequencies throughout THz spectral range with sufficient power levels. Furthermore, development of table top THz sources would be a major milestone towards enabling THz technologies to be transferred from the lab setting into real market applications [2].

In order to realize such extremely efficient, inexpensive and compact CW THz sources, photomixing of two wavelengths based on diode lasers is currently one of the promising potential techniques. Moreover, it has been demonstrated in the past that it is possible to generate THz radiation from a two color diode lasers without external mixing elements directly at ambient temperature conditions [7], [8]. This thereby provides an extremely compact THz source and cheap system operating at room temperature but the THz power generated with such a system was in a few magnitude. Hoffmann et al., analyzed the restricting factors to access the THz bandwidth as well as the semiconductor nonlinearity of a two color diode in generating THz signal. The results demonstrated that the gain medium doesn't limit the bandwidth, since the operation of the diode was possible up to 30.2 THz optical beat frequency and even the carrier response exhibited a nonlinear response of up to 4.2 THz [9]. Further experiments and theoretical analysis have suggested some technological efforts to enhance the power generated from a two color diode lasers to application levels by improving on the design of the diode structure [8]. However, the confirmed nonlinear response of the carrier system to THz frequencies introduces the possibility for further applications, such as THz detection using laser diodes. This would be of high interest in the development of a whole THz system, which demands that both a THz emitter and a THz receiver to be as small as possible. Recently, it was indeed demonstrated in first proof of principle studies [8] [10], that semiconductor diode lasers can not only generate but also, they can detect THz radiation. The realization of diode laser based THz sources and detectors, will offer the prospects of building a very compact and complete THz systems on a single optoelectronics substrate [8].

The motivation in this dissertation was to investigate how THz radiation interacts with the charge carriers in diode lasers and, in particular, to demonstrate THz detection using semiconductor lasers. The experimental work was to realize an optimized detection scheme enabling THz spectroscopy using commercially available semiconductor lasers diode. This could add new potential capabilities applications in fields such as security sensing, spectroscopy, imaging, material research and communications. Further work, was to implement compact and cost efficient THz sources based on two color semiconductor diode lasers via the process of photomixing and contribute in development of THz systems with capability of enabling the transfer of THz technology from the lab setting into real world application.

1.1 Organization of this dissertation

This dissertaion is structured into six chapters. The general introduction of this dissertation and the motivation of doing this research investigation is provided in chapter 1. In chapter 2, we describe the fundamentals of the semiconductor diode as well discuss the operation of semiconductor diode laser. A few types of diode lasers more so the ones used in this study are highlighed with their key features and operation principles discussed. In chapter 3, different detection schemes and how they operate with an analysis on the need to develop new compact detection approaches in order to make THz detection available for application is given. Chapter 4, describes the study of the interaction of THz radiaton from different THz sources with a semiconductor diode arranged in Littman configuration. The motivation being to demonstrate a compact detection scheme of THz radiation with diode laser and preliminary findings on our experiment are given. In chapter 5, the fundamentals and mechanism of THz generation with photoconductive antennas is discussed. The implementation of compact THz sources based on the use of monolithically integrated DBR lasers emitting two modes simulteneously as an excitation source for photoconductive antenna is discussed. In this study two laser diodes are discussed, One was tunable via temperature changes of the laser chip plus the diode submount while the second was electrically tunable via carrier injection to the laser chip alone. More details on the operation of these devices will be given and their potentail use for CW THz generation is presented. Finally the results on the developed THz systems will be given with potential application in non-destructive moisture measurements, moisture monitoring on drying process of pieces of paper, THz spectrocopy such as characterization of THz filter and THz metrology such as thickness measurement of polyethylene sample will be discussed. Lastly, a concise summary of the entire dissertation is described in chapter 6.

Chapter 2

Fundamentals

In this chapter, semiconductor diode laser which is one of the key components used in the study carried out in this dissertation is discussed. The fundamental aspects and operation of a semiconductor diode laser are presented. A few types of diode lasers, more so ones used in this research are introduced with their operation principle and key features highlighted.

2.1 Semiconductor diode laser

A semiconductor laser is an electronic device that radiates light signal when a forward bias is applied across its p-n junction resulting to the flow of a current. Semiconductor lasers were first developed in the earlier 1960's [11] and over time diode lasers have developed into key components in modern optoelectronics and photonics technology. In our day to day applications, diode lasers have found their way into compact disc systems (for data storage), pointers, printers, bar code scanners, and optical communications for the transmission of information through optical fibers. Furthermore, they have gained use in the studies of atomic structure and quantum-mechanical effects and more recently they are gaining applications in other emerging fields such as THz generation and detection [8] [10] [12],Raman spectroscopy [13], photoacoustic imaging [14], optical coherence tomography [15] and Biophotonics [16]. Our focus here was to use semiconductor diode lasers as key development tools to generate THz signal as well as a THz detector. The following features distinguishes diode lasers from other lasers: They are compact, diode lasers are quite small in size, the small size footprint enables them to be easily integrated into many instruments. They are highly efficient (around 50% efficiency) which makes them to be driven by low injection currents. As they can be manufactured in large quantities they are cheap. Furthermore, mass production of diode lasers is cost effective hence they are affordable for various applications. Finally, semiconductor diode lasers can be tailored to emit particular wavelengths. Most lasers are usually limited to a specific atomic transition, therefore their emission wavelength is defined. While, diode lasers can be designed to emit wavelengths covering the broad frequencies of the electromagnetic spectrum [16], depending on the composition of the different combinations of the elements of group III-V semiconductors. Table 2.1 gives some common alloys on semiconductor substrate and their corresponding laser wavelength emission.

Compound	Spectral range	application
$Al_xGa_{1-x}N$	uv	
GaN	uv 350 nm	
$In_xGa_{1-x}N$	blue 400-480 nm	data storage, display
$In_xAl_yGa_{1-x-y}P$	red 615-750 nm Ref [15]	display
$Ga_xIn_{1-x}P(x = 0.5)$	670 nm	display
$Ga_xAl_{1-x}As(x = 0 - 0.45)$	620-895 nm	
$Al_xGa_{1-x}As_{1-y}P_y$	670-890 nm Ref [15]	
GaAsP	785 nm	Raman spectroscopy Ref [13]
GaAs	904 nm	diode pumping
$In_xGa_{1-x}As(x = 0.2)$	980 nm	solid-state and fiber lasers
$In_xGa_{1-x}As_yP_{1-y}$	1110-1650 nm	communication
(x=0.73, y=0.58)	1310nm	
(x=0.58, y=0.9)	1550nm	

Table 2.1: Table of semiconductor compounds for the manufacture of different diode with different wavelength emission [17].

The selection of different or a particular wavelength emission for a certain compound structure is perfomed by course adjustment of the various combinations of the molfunction x, y and z. With several combinations of group III-V compounds a broad spectral range can be covered [15]. In this study we employ structures made of GaAsP/GaAs emitting at 785 nm (for THz generation experiments) and GaAs/AlGaAs emitting at 840 nm (for THz detection experiment) respectively.

2.1.1 Energy bands

In a semiconductor material, the interactions of atoms split the discrete energy levels into distinct energy levels, which are closely spaced in energy forming a continuous band of energy state commonly referred as energy band. The electrons can occupy this energy bands. In thermal equilibrium, the uppermost band which is empty of electrons is the conduction band (CB). The CB is distinct from the next lower level called valence band (VB) which is full of electrons, by a transition energy referred as bandgap energy E_g. Electrons can move from the VB to CB, when a semiconductor materials is supplied with an energy exceeding the E_g [18].

At absolute zero, Fermi levels are used to describe the energy occupance of electrons. A semiconductor material with majority of holes is called p-type and has a Fermi level E_{FP} which is close to the VB while a semiconductor material with majority of electrons is an n-type and its Fermi level E_{FN} is close to CB. The joining of p-type semiconductor material back to back with an n-type semiconductor materials forms a sandwich commonly referred as a p-n junction. A p-n junction is what is termed a diode. Figure 2.1 summarizes the basic operation of a diode depended on the applied bias. At zero bias Figure 2.1(a), the Fermi level across the diode is continuous therefore the Fermi levels are equal $E_{FP} = E_{FN}$. The free electrons and holes in the junction diffuse resulting to a zone free of electrons and holes forming the so called depletion layer. An in build voltage V_o which is generated as a result of this recombination prevents the electrons and holes from transiting from one side of the junction to the other. Across the junction if a forward bias V

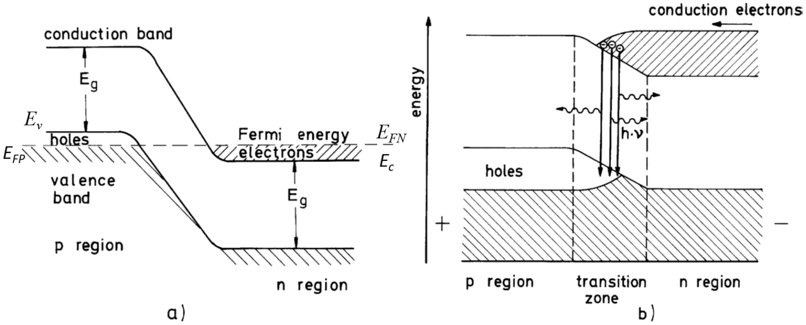


Figure 2.1: The energy band diagram of a p-n junction (a) when not biased and (b) when forward biased [21].

is applied, the Fermi level is split into Quasi-Fermi levels, and is not continuous any more [19] [20]. Therefore the electrons and holes are free to transit the depletion region. As electrons recombine with the holes, they release a photon of energy $h.v$ when stimulated emission occurs as shown in Figure 2.1(b) [21]. Over time a p-n junction was found not to be efficient enough hence resulted to the development of another structure the so called double-heterostructure [23]. This structure is based on an active laser material sandwitched between a material with large bandgap. As a result the charge carriers and the photons are constricted into the active region which makes the laser diode to be operated with low injection current [24].

One of the most widely developed diode lasers are based on the GaAs/AlGaAs semiconductor material. They comprise of a GaAs active layer embedded within layers of AlGaAs which serve to confine the laser radiation. The two opposite faces are then smoothened, cleaved, and made parallel with respect to each other. These facets, act as resonant mirrors which provide the feedback desired for laser action. For laser action to occur the p-n junction is pumped by an electrical current commonly referred as the injection current. At the center of the diode structure is the active region, when an injection current passes other layers and reaches this region, electrons are accelerated and transit from the VB to the CB, in the process a population inversion is created resulting to emission of photons when the electrons and holes under go stimulated emission [22]. The burying layer or current blocking layer restricts the current to a narrow strip which ensures low current injection for laser action with a single lateral mode [20]. A schematic structure of semiconductor laser with a double heterostructure is shown in Figure 2.2.

The electrons distribution in the conduction band and valence band is governed by their Quasi-Fermi energy which is determined by their population. The probability of electrons occupying a particular energy levels in the conduction band is described by the Fermi-Dirac function [2, 24]:

$$f_{cb}(E) = \frac{1}{1 + \exp\left(\frac{E - F_n}{k_B T}\right)} \tag{2.1}$$

and in the valence band

$$f_{vb}(E) = \frac{1}{1 + \exp\left(\frac{E-F_p}{k_B T}\right)} \tag{2.2}$$

where E_v and E_c are the allowed energy states in the VB and the CB respectively, and F_n and F_p are their corresponding Quasi-Fermi energy levels, T is the absolute temperature and k_B is Boltzmann constant.

A particular Quasi-Fermi level position depends on the temperature and the density of electrons and holes. Should the following condition

$$E_g < E_2 - E_1 = \frac{h}{2\pi}\omega < F_c - F_v \tag{2.3}$$

be satisfied, the recombination of charge carriers will dominates the absorption and other losses hence laser action will take place due to stimulated emission [2]. Another important requirement to be fulfilled for stimulated emission to be observed is the active region must be a direct band gap seimconductor where stimulated emission can occur. In addition to that, the charge carrier population within the active region should be sufficient such that their Quasi-Fermi levels are discrete by an energy greater than that of the emitted radiation [11].

The semiconductor band structures are categorized into two groups. The first band structure is a direct bandgap structure, which is the band in which the maximum energy level of the valence band falls within the same wavevector k space or at same crystal momentum with the minimum energy state of the conduction band. The transition of electrons takes place along the zero point of the wavevector ($k = 0$) space with the momentum conservation law satisfied. The second band is indirect bandgap structure in which the minimum energy level of the conduction

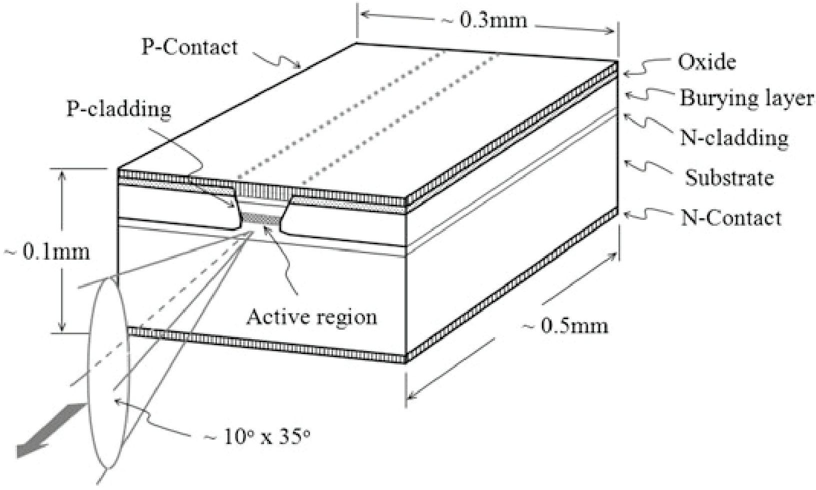


Figure 2.2: Schematic of typical laser diode chip, cladding is AlGaAs, active region is GaAs. Burying layer restricts current flow to narrow stripe perpendicular to the slit, through active region [25].

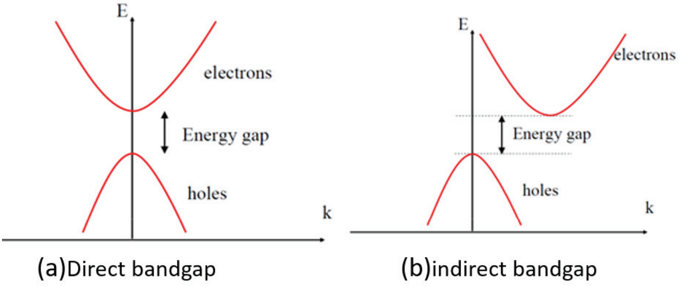


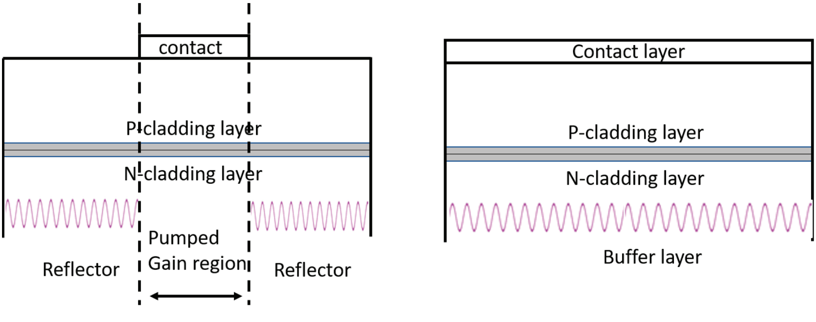
Figure 2.3: The bandgap materials types in semiconductor structure [26].

band doesn't lie in the same vector space with highest energy state of the valence band. This makes it challenging to obtain a transition of electrons easily hence even with alot of current pumping it is impossible to achieve stimulated emission in indirect band gap. Most of group III–V compounds such as InGaAsP, AlGaAs, InP,and GaAs belong to the direct band gap material, while Si and Ge are materials in the indirect category [17, 27]. Figure 2.3 shows the schematics of the two band gap transitions in wavevector space.

2.1.2 Different semiconductor laser structures

Semiconductor lasers (SLs), can be directly pumped and emit photon either from the edge or from the surface of their structure. The structures in which the emission of the light signal is from the top surface with the direction of the signal being perpendicular with respect to the surface substrate are said to be surface emitting lasers examples of lasers in this category are the vertical cavity surface emitting lasers (VCSELS). While structures that enables the light signal to travel along the wafer surface of the semiconductor substrate are the edge emitting lasers. Due to the differences in refractive index between the burying and the active layers, the carriers and the photon are confined along the active layer region [15]. With gain guided structures(i.e with restricted current pumping) or by implementing index-guided structure in which lateral step index is designed one can obtain lateral confinement of the optical modes. However, with a lot of progress in growth techniques, quantum well (QW) structure with reduced active layer thickness have been realized. They exhibit low threshold current and excellent modulation features. Most of the available diode lasers in the market are made from QW structures [2].

The structures can emit either a single mode or multiple modes depending on the number of wavelengths they are able to select. The Fabry Perot Laser (FP-laser) structures have no wavelength selection devices hence they usually emit multiple wavelengths. This causes the laser to lase at higher modes and permits the laser to oscillate between different longtudinal modes. In such structures the laser exhibits low coherence and large linewidths. In order to avoid this, it is necessary to have wavelength selection in the laser under which it operates. This can be achieved by inserting a wavelength selective optics to select only single frequency and eliminate other frequencies. This is achieved through incorporating periodic gratings struc-



(a) DBR laser

(b) DFB laser

Figure 2.4: Schematic diagram of (a) DBR laser and (b) DFB laser semiconductor structures [24].

tures within the laser waveguide which enables a single laser emission at any given time. Such structures are grouped into; Distributed Feedback (DFB) lasers which are structures which incorporate grating structures in the active region, and Distributed Bragg Reflector (DBR)lasers which are structures which incorporates the grating in the passive region [19, 24]. DFB and DBR lasers operate in a single frequency even under pulsed mode with narrow linewidth and highly coherent signal, in contrast to FP-lasers, which exhibit several wavelengths when operating in pulsed mode [19]. We employed two DBR lasers structures emitting two colors simulteneously at 785 nm center wavelength to demonstrate THz generation. Figure 2.5 shows a vertical layer structure of the two-color DBR laser used in this study. The active region was made up of GaAsP semiconductor material which was sandwitched between two waveguide layers made of AlGaAs and two cladding layers. The AlGaAs layer has a thickness of 500 nm while the cladding layer is 1μm. The whole structure is grown on GaAs substrate by metal organic vapour phase epitaxy (MOVPE). More details on the design and fabrication of this structure are described in ref [28, 29]. We employed such structures to demonstrate THz emission via photomixing in ion implanted log-spiral photoconductive antenna. Detailed investigation of the use of this structures for applications in THz generation is discussed in chapter 5.

DFB and DBR structures can be tunable with either temperature (course tuning) or via current (fine tuning) which enables the refractive index to be varied along the active region in the process changing the emission wavelength of the laser. Wavelength selection via temperature may result to instabilites due to mode hopping and usually tunability of such structures is limited. Wide tuning of the emission frequency in the SLs can be achieved not with DFB/DBR but with FP-lasers by employing external cavity configuration, incorporating the use of diode laser as the laser gain medium, wavelength filter for selection of the laser mode and an end mirror to provide the optical feedback. There are two main categories of external cavity configurations namely the Littman-Meltcalf configuration and the Littrow configuration. A diffraction grating is commonly used as the wavelength selector and enables a broad tuning across the gain region of the diode. A semiconductor

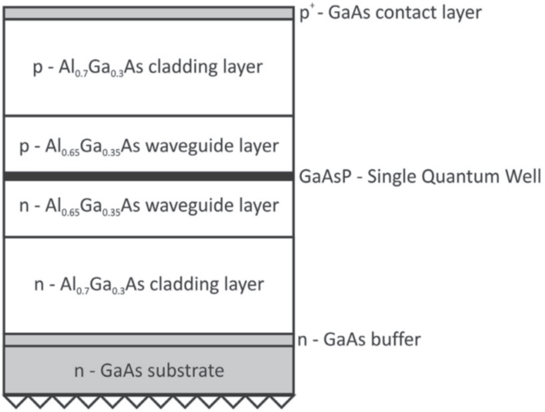


Figure 2.5: Schematic illustration of vertical layer structure of two-color DBR lasers used in this study [28].

laser having its front facet deposited with an antireflection coating (AR) while its rear facet is deposited with high reflecting (HR) coating is used as the gain medium. An optical feedback from the diffraction grating is sent back into the diode through the lens and consists of reflected mode with narrow linewidth than the beam which was incident at the grating. Stimulated emission is induced by the reflected signal in the diode gain medium at the wavelength of the feedback beam. The diode then lases at the wavelength of the feedback signal at a much narrower linewidth better than that of the incident signal [30]. Figure 2.6 shows the two external cavity configurations. In Littrow configuration, mode selection is done by the adjustment of the grating while in Littman-Meltcalf configuration the wavelengths are selected by tuning the additional end mirror introduced in the cavity while the diffration grating remains fixed [31].

As mentioned before, the grating acts as a wavelength selector providing the desired optical feedback. Figure 2.7 shows a blazed grating in which a light signal is incident at the diffraction grating. The angle of incident is α, while the angle at which the beam is diffracted is β. In Littrow configuration, the angle of incidence equal to that of reflection. Therefore at any given time the order of the diffrated beam is sent back and travels along the path of the incident beam. According to the grating equation the following condition should be met for constructive interference to occur [30].

$$d(sin\alpha + sin\beta) = m\lambda \tag{2.4}$$

where d is the spacing of the grooves, λ is the wavelength of the incident signal and m is the order of diffraction of the beam. In Littrow configuration $\alpha = \beta$, therefore equation (2.4) reduces to

$$m\lambda = 2dsin\alpha \tag{2.5}$$

The blaze wavelength λ_B, which is the wavelength where much of the optical power or energy is concentrated which is commonly referred as the first order diffracted