

DISTRIBUTED WAVEGUIDE DESIGN FOR REDUCING THERMAL LOAD IN SEMICONDUCTOR HIGH POWER LASERS

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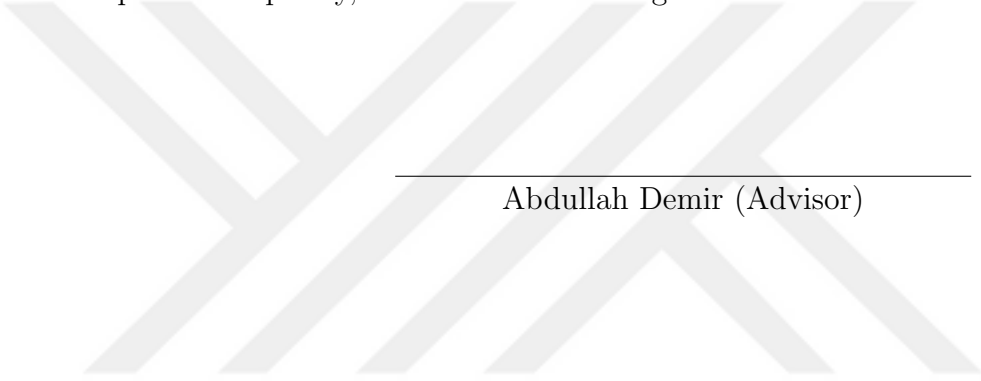
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January 2025

Distributed waveguide design for reducing thermal load in semiconductor high power lasers

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January 2025

We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.



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ABSTRACT

DISTRIBUTED WAVEGUIDE DESIGN FOR REDUCING THERMAL LOAD IN SEMICONDUCTOR HIGH POWER LASERS

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M.S. in Materials Science & Nanotechnology

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Semiconductor lasers lead laser technology due to their high efficiency, compact size, and cost-effectiveness. Among these, GaAs-based laser diodes (LDs) are the most efficient light sources, but are still constrained by self-heating, which elevates internal temperatures and degrades performance, output power, and device lifetime. Traditionally, increasing the cavity length has mitigated this issue by improving thermal conductivity, facilitated by advances in epitaxial growth, design, and device packaging. However, the cavity lengths of high-power GaAs LDs are now limited to approximately 5 mm, beyond which the output power declines because of intrinsic physical constraints.

This work presents a new type of waveguide design, called distributed waveguide (DWG), that overcomes conventional cavity-length limitations. The DWG integrates lasing and secondary sections along the waveguide, which are electrically isolated to control current injection, yet optically connected for efficient beam transport. The laser section is electrically pumped to generate output, while the secondary section operates near-threshold to dissipate heat effectively. Extending the cavity length from 4 to 8 mm, DWG LDs exhibit significantly improved thermal management with favorable device characteristics. Experimental results, corroborated by numerical analysis, demonstrate that DWGs achieve approximately $1.8\times$ lower junction temperature change while delivering high output power. Additionally, the DWG platform and its fabrication process are fully compatible with standard semiconductor laser manufacturing techniques, ensuring industrial adoption. This work provides clear evidence that innovative waveguide designs can effectively mitigate self-heating, promising enhanced performance, output power, and reliability in semiconductor lasers.

Keywords: semiconductor laser, high power, diode laser, heat management, waveguide design, distributed waveguide.



ÖZET

DAĞITIK DALGA KILAVUZU TASARIMI İLE YÜKSEK GÜÇLÜ YARIİLETKEN LAZERLERDE ISIL YÜKÜN AZALTILMASI

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Yarıiletken lazerler, yüksek verimlilikleri, kompakt boyutları ve düşük maliyetleri sayesinde lazer teknolojisine öncülük etmektedir. Bu lazerler arasında GaAs tabanlı lazer diyotlar (LD), en verimli ışık kaynakları olmalarına rağmen kendiliğinden ısınma nedeniyle hâlâ bazı kısıtlamalara sahiptir. Bu kendiliğinden ısınma, iç sıcaklıkların artmasına yol açarak performansın, çıkış gücünün ve cihaz ömrünün azalmasına neden olur. Geleneksel olarak, epikristal büyütme, tasarım ve paketlenme teknolojilerindeki gelişmeler sayesinde kavite uzunluğunun artırılması ile termal iletkenlik iyileştirilmiş ve bu sorun hafiflemiştir. Ancak günümüzde yüksek güçlü GaAs LD'lerin kavite uzunluğu içsel fiziksel kısıtlamalar nedeniyle yaklaşık 5 mm ile sınırlı kalmakta; bu değerin üzerine çıkıldığında çıkış gücünde azalma gözlenmektedir.

Bu çalışma, geleneksel kavite uzunluğu sınırlamalarını aşan yeni bir dalga kılavuzu tasarımı olan “dağıtık dalga kılavuzu” (DWG) kavramını tanıtmaktadır. DWG, dalga kılavuzu boyunca lazer ve ikincil bölümleri bütünleştirir; bu bölümler elektriksel olarak birbirinden izole edilerek akım enjeksiyonu kontrol altına alınır, ancak ışının verimli taşınması için optik olarak bağlantılıdır. Lazer bölümü, istenen ışık çıkışı üretmek amacıyla elektriksel olarak pompalanırken, ikincil bölüm lazer eşik akımı yakınında çalıştırılarak ısının etkin biçimde dağıtılmasını sağlar. Kavite uzunluğunun 4 mm'den 8 mm'ye çıkarılmasıyla DWG LD'ler, önemli ölçüde iyileştirilmiş termal yönetim ve cihaz özellikleri sunmaktadır. Deneysel veriler ve sayısal analizler, DWG'lerin yaklaşık 1,8 kat daha düşük lazer gövde sıcaklıklarında çalıştığını göstermektedir. Ayrıca DWG platformu ve üretim süreci, endüstriyel uygulamaları kolaylaştıracak şekilde standart yarıiletken lazer üretim teknikleriyle tamamen uyumludur. Bu çalışma, yenilikçi dalga kılavuzu

tasarımlarıyla kendiliğinden ısınmanın etkili biçimde hafifletilebileceğini ve bu sayede yarıiletken lazerlerde daha yüksek performans, çıkış gücü ve güvenilirlik sağlanabileceğini açıkça göstermektedir.



Anahtar sözcükler: Yarı iletken lazer, yüksek güç, diyot lazer, ısı yönetimi, Dağıtılmış dalga kılavuzu, dalga kılavuz tasarımı.

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Chapter 1

Introduction

The word laser refers to Light Amplification by Stimulated Emission of Radiation which was first used by Gordon Gould and the experimental demonstration was done by Theodore Maiman in 1960 [1]. Ruby lasers were the first type of lasers discovered by Maiman. Later, Gas-based lasers were discovered such as CO_2 lasers, He-Ne lasers. The drawback of these laser systems is low conversion efficiency and huge size. Overcoming these issues, semiconductor-based lasers came to light with compact size and higher conversion efficiency [2, 3, 4, 5, 6]. The first ruby laser developed by Maiman and the semiconductor based lasers later developed, differ in their pumping. While both are solid-state lasers, the former is optically pumped with low efficiency, and the latter is electrically pumped with higher efficiency. Since the development of molecular beam epitaxy (MBE) and metal organic chemical vapor deposition (MOCVD), semiconductor laser technology has progressed a lot owing to the deposition of semiconductor material layers with desired compositions [1, 7], which made these devices highly demanded in multiple applications, including telecommunications, fiber lasers, medicine, and material processing [8, 9, 10, 11, 12, 13].

1.1 Laser Principle

An optical amplifier is a device that boosts the amplitude of an optical field with phase preservation. A semiconductor optical amplifier inside an optical resonator is referred to as laser diode, where the optical amplifier is fabricated with a semiconductor material of direct band-gap. There are three elements which are required to generate laser light.

- Active Medium/Region (AR):

AR converts the pumped energy into laser light

- Pumping Source:

It is the source of energy for exciting the electrons in the AR

- Feedback Mechanism:

AR has a higher index of refraction than the surrounding creating highly reflective mirrors and forming an optical cavity inbetween the mirrors

The reflectivity of the facets is equal which can be altered by coating the facet. For an industrial laser diode, one of the facet is coated, increasing the reflectivity of that facet so there would be more transmission of laser light from the opposite facet. The mirror coating leads to higher output optical power through the out-coupling facet having a lower reflectivity. The configuration of before-mentioned components enable the operation of LASER which can be seen in Figure 1.1.

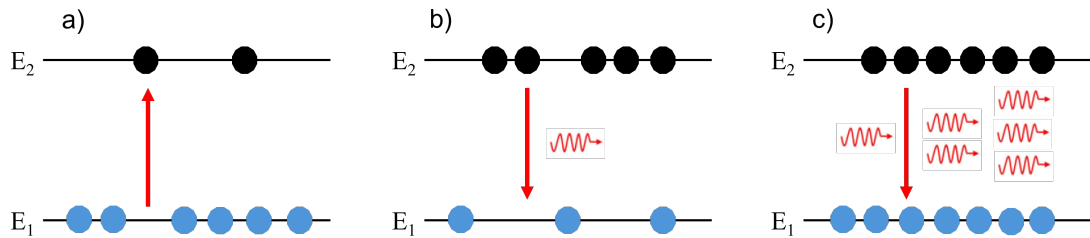


Figure 1.1: a) Absorption (b) Population inversion achieved by electron excitation (c) Light amplification through stimulated emission.

The laser operation is performed in three steps.

- **Absorption:**

The pumped energy is absorbed by the active medium and used to excite the electrons from the stable ground state E_1 to the excited state E_2 as shown in Figure 1.1 (a).

$$N_1 > N_2$$

With enough energy absorption the system reaches a state called population inversion in which the number of electrons are more in excited state (N_2) as compared to ground state (N_1).

$$N_2 > N_1$$

- **Spontaneous Emission:**

When the system reaches population inversion, electrons in the excited state de-excite and go back to the ground state while releasing a packet of photon, depicted in Figure 1.1 (b). The energy of the photon is equal to the band-gap difference between the ground state E_1 and the excited state E_2 , and the wavelength also depends on the band-gap [7, 14] as shown in the equations below

$$E_{\text{photon}} = \Delta E_{12} = E_g = hf \tag{1.1}$$

$$E_g = \frac{hc}{\lambda} \tag{1.2}$$

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T + \beta} \tag{1.3}$$

where h is Planck's constant, f is the frequency of the photon, λ is the wavelength of the emitted photon, T is the operating temperature, E_g is the bandgap energy, α is the temperature coefficient, and β is a material-specific parameter.

- **Stimulated Emission:**

The previously emitted photon stimulates the electrons in E_2 excited energy state to transition to the lower/ground energy state E_1 , thus emitting a photon. The emitted photon is identical in properties (frequency, phase, and amplitude) to the stimulating photon. The process undergoes continuous excitations and de-excitations of electrons to generate more and more photons.

Photons generated through electron de-excitations reflect back and forth in the optical cavity as shown in Figure 1.2.

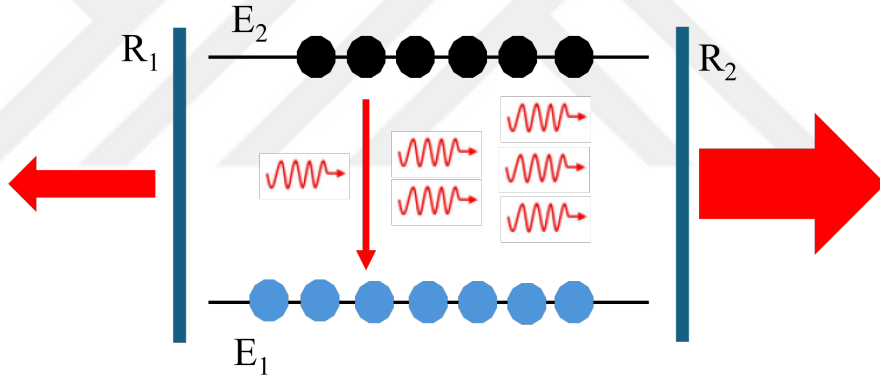


Figure 1.2: Schematic of optical cavity.

As already mentioned, population inversion is a prerequisite for initiating lasing in the optical cavity[15]. Another important condition for lasing is that the gain should become higher than the total loss occurring in the resonator. The gain required to initiate the lasing is called threshold gain g_{th} which is shown by equation 1.4.

$$g_{th} = \gamma + \frac{1}{2L} \ln \frac{1}{R_1 R_2} \quad (1.4)$$

Here, L represents the length of the cavity with R_1 & R_2 as the reflectivity of the facets, and γ is the total loss coefficient. According to equation 1.4, the

optical amplification will occur when g_{th} is greater than the total loss in the optical cavity. The laser light generated in the optical cavity has three significant properties that makes the laser device differ from other light sources.

- Coherency:

The laser light is highly coherent which means that each individual light wave is in phase with each other.

- Mono-chromaticity:

The output laser light has a single wavelength or in a very narrow range of wavelengths

- Collimation:

The divergence of laser light is low as compared to other sources of light and thus is well collimated.

1.2 Thermal effects

In an ideal scenario, all devices (electronic and optoelectronic) would perform at 100% efficiency. However, in reality, every working device has some inherent loss that cannot be avoided and even with the unavoidable losses, semiconductor-based lasers perform proficiently well with a high efficiency ranging from 60 - 80 %. The other 20 - 40 % not converted is the loss, increasing the thermal load on the device. However, with better heat dissipation, facet coating, and improved epitaxial designs, the efficiency can be improved. Another approach to scale the output power of LDs is to increase the cavity length which has usual limit of 5-6 mm, by lowering the internal loss to 0.30/cm as is done by Liu et al [16]. However, the increase in cavity length also give rise to various degradation phenomenons, one of the most disastrous being spatial hole burning (SHB) and it limits the cavity length to 6mm[17, 18, 19]. Now, the problem becomes significant when these devices are operated at higher currents. The input power (P_{inp}) that is

not converted to the output optical power (P_{out}) transforms into waste power (P_{waste}).

$$P_{input} = P_{out} + P_{waste} \quad (1.5)$$

The waste power P_{waste} , considered as the loss, is converted to heat energy, thus raising the temperature of the active region of the diode laser, and this phenomenon is referred to as self-heating. Therefore, the self-heating of diode lasers is an intrinsic problem, and the temperature increase from self-heating affects detrimentally the characteristics and performance of semiconductor lasers. In the last two decades, semiconductor laser technology has progressed considerably, but heating-induced failure of diode lasers remains one of the major limiting factors in device performance.

1.2.1 Impact on Performance

In this section, the impact of temperature on the performance of the laser diode is discussed. For a semiconductor material, the effect of temperature is significant in properties such as electron mobility, refractive index, current distribution, current injection, energy band structure, and gain saturation, leading to spatial hole burning (SHB), and catastrophic optical damage (COD)[20, 21, 22]. From a different perspective, the active region of a laser diode is more prone to changes owing to the temperature increase as compared to other layers in the epitaxial structure. Ma et al.[23] studied the threshold current and carrier density sensitivity as a function of temperature for a 1.55 μm laser diodes. Kanazawa et al.[24] worked on the temperature sensitivity for a 1.2 μm laser diode under high temperatures. Li et al.[25] investigated the temperature dependence for a 1.06 μm laser diode based on InGaAs/InGaAsP quantum well. Liao[26] et al. researched a 940 nm laser diode in the temperature range of 13°C to 60°C. Huang et al[27] reported the temperature effect on an 850 nm laser diode. There have been numerous studies showing the effect of temperature on the output power of

diode lasers [28, 26, 29, 30, 31, 32, 33, 34].

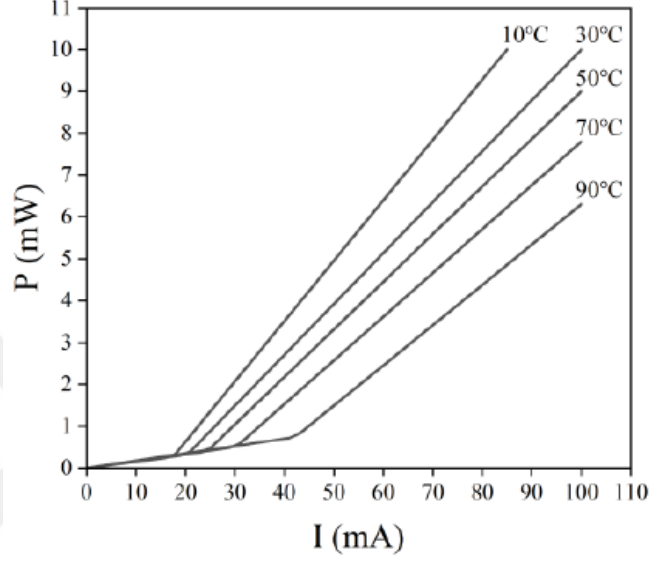


Figure 1.3: Decrease in output power as a function of heatsink temperature [35].

As the temperature of the diode laser increases, a decrease in the output optical power occurs as can be seen in the Figure 1.3. In a study by Hasler [36], the accumulation of free carriers dropped and the mode gain improved at 200 K, which led to the improvement in slope efficiency and also reducing the threshold current. The increase in temperature of semiconductor results in the exponential increase of non-radiative recombination rate above 300 K and the recombination rate of electron hole drops exponentially as well. Since the non-radiative recombination in the active region increases with temperature and the recombination rate decreases, it results in the accumulation of heat and a decrease in the output optical power, respectively [37, 38]. The decrease in output power can also be attributed to the defects in the laser which can diffuse at high temperatures. Nevertheless, defect diffusion is an irreversible phenomenon that significantly impacts the reliability of semiconductor lasers. Wang et al.[39] studied the optical power, spectral variation, and power conversion efficiency from 0 to -60°C. The carrier leakage reduced at lower temperature as the carriers' energy distribution became narrower. Along with optical loss and transparent carrier concentration, the threshold current reduces at lower temperature. The threshold current I_{th} is

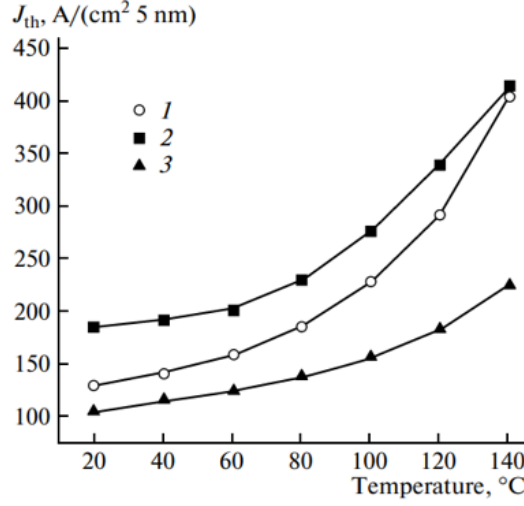


Figure 1.4: Threshold current dependency on temperature for three different epitaxial designs [40].

affected by the temperature of a diode laser, as shown in the equation 1.6.

$$I_{th}(T) = I_{th}(T_o) \exp\left(\frac{T - T_o}{T_o}\right) \quad (1.6)$$

The threshold current depends on the radiative recombination in the active region and since the radiative recombination decreases with increasing temperature, a higher injection current is required to achieve the threshold current density [40, 28, 26, 31, 37].

Pikhtin et al [40] studied the optical losses for a 920 nm LD and their dependency on the temperature. He used three different epitaxial designs to investigate the effect of temperature. An increase in threshold current density was observed along with a decrease in the quantum efficiency at higher temperatures. It is proposed that at high temperatures, the confinement of charge carriers is insufficient, leading to an increase in optical losses and a lower quantum efficiency. In another study by Wu et al [28], the loss in optical power and an increase in I_{th} is shown with increasing temperature for a 808 nm LD, both experimentally and simulated. Their argument for the decrease in slope efficiency and threshold current density is the carrier confinement efficiency which decays at higher temperature. The loss in quantum efficiency, output power, and higher current threshold prompts a decrease in the power conversion capability of semiconductor

laser. In 2017, Song et al[33], conducted an experiment to analyze the efficiency of an 808 nm diode array. The electro-optical power conversion efficiency was calculated for a temperature range of -40°C to 25°C .

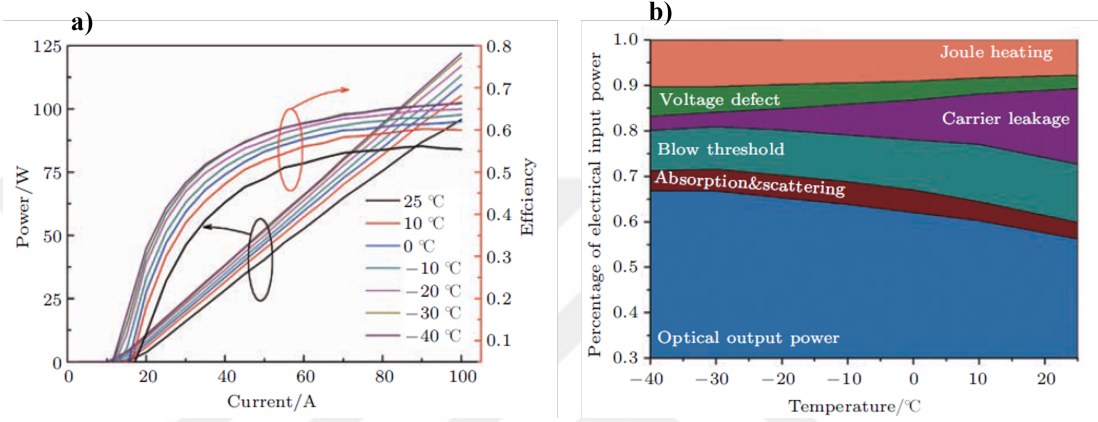


Figure 1.5: (a) LI and PCE analysis for varying temperature (b) energy loss analysis [33].

The PCE was found to increase from 56.7 % to 66.8% as the temperature dropped from 25°C to -40°C . Furthermore, the carrier leakage ratio also decreased from 16.6% to 3.1%, which implies that the primary reason for higher power conversion efficiency is the reduction in carrier leakage loss. In this temperature range, an energy loss analysis was performed to investigate the factors limiting the electro-optical conversion efficiency (shown in Figure 1.6 b). The output optical power drops with an increase in temperature as a result of loss of efficiency. Most of the electrical input energy is wasted because the loss from carrier leakage increases considerably with temperature. Meanwhile, the loss from joule heating, voltage defect, absorption & scattering remain relatively constant. In a recent study, Wu et al[28] investigated in detail (experimentally and theoretically) the effect of temperature on an 808 nm laser array. The optical loss did not change significantly when the injection current increased from 0 to 10 A. Although as the temperature increased from 223 to 323 K, the increase in optical loss was exponential. The high optical loss is related to the high carrier concentration requirement in the quantum well. As the material gain decreases with increasing temperature, more carriers are required to reach the new threshold gain. Figure

1.6 shows the lasing spectrum as a function of temperature. Eq. 1.2 shows that a photon's wavelength and the active region's band gap are inversely proportional and it is evident from Eq 1.3 that increase in temperature reduces the bandgap energy of the semiconductor.

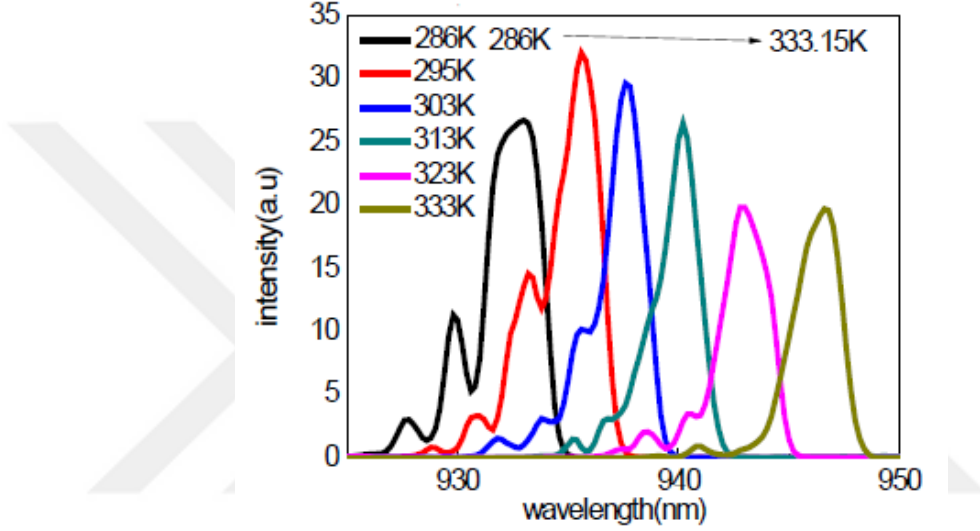


Figure 1.6: Shift in spectrum with temperature[26].

1.2.2 Degradation Modes

Hence, to mitigate the poor performance associated with thermal effects, we need to understand the degradation modes in a diode laser. The degradation modes can be categorized over a time scale.

- **Rapid degradation:**

The type of degradation that manifests during the first 100 hours of lasing. The degradation causes a sudden threshold current I_{th} increase or a sudden decrease in the output optical power P_{out} . The cause of rapid degradation is the defects generated during the manufacturing of the laser diode.

- **Gradual Degradation:**

The degradation spans over thousands of hours and is depicted by a slow & gradual decrease in the output optical power, which results from the decrease in the efficiency. Gradual degradation is associated with point defect generation and diffusion of these defects over long periods of time which results in gradual increase in non-radiative recombination. The previously present point defects assist in the creation of new point defects, thus slowly decreasing the performance of the device.

- **Catastrophic degradation:**

Catastrophic degradation is observed when a certain threshold condition is met. The result of this degradation mode is a sudden loss in either total output power or a substantial decrease due to the structural deformities manifested in the device. When the device absorbs the optical emission, the resultant catastrophic damage is then called as catastrophic optical damage (COD). It can occur both at the facets (catastrophic optical mirror damage) or within the bulk of the diode laser (catastrophic optical bulk damage).

1.3 Heat management strategies in LDs

Despite the improved photoelectric conversion efficiency of semiconductor lasers compared to other laser types, the demand for higher power and more compact structures has substantially enhanced the demanding nature of their heat management technique. Elevated power density output will induce significant heat flux in the laser, adversely impacting its performance metrics, including efficiency, power, wavelength, and reliability. Consequently, investigations into heat dissipation strategies for high-power semiconductor lasers remain significant.

In traditional heat dissipation methods, natural convection cooling employs metals with high thermal conductivity, such as copper heat sinks [41], and diamond heat spreaders [42] to enhance the heat dissipation area of the laser chip, hence improving heat dissipation and lowering the chip's temperature. Heat sink

performance can vary depending on the structure and material used. In a study by Yuncu et al [43], heat dissipation is investigated for a heat sink with fins. The impact of the spacing between the fins and their height on heat dissipation is determined through study. At a steady temperature, the increase in fin height reduces the ideal fin spacing. The heat sink is suitable for a 50 W laser with great efficiency. A few other studies confirmed the height and fin spacing as the main parameter affecting the heat dissipation rate in fin-type heat sinks [44, 45, 46]. For the same fin-type heat sink, Meng et al[47] reported the relation between mounting angle and heat dissipation. According to the research, the heat dissipation effect is weakest at 15° installation angle and best at 90° angle. It has been determined that properly trimming the edges of the heat sink fins can enhance the heat transfer coefficient and lower specific thermal resistance. This heat dissipation is only appropriate for low-power semiconductor lasers owing to its limited capacity and generally slow heat dissipation rate.

For a high-power semiconductor laser, the thermal load is also high which brings the need for a cooling system with high heat dissipation. Researchers have forced natural convection by introducing a water-cooling channel in the heat sinks to decrease the high heat load on devices. Such a system works with a liquid coolant to dissipate the heat generated in the electric and optoelectronic devices [48, 49, 50]. This approach provides a much better efficiency in heat dissipation compared to previously discussed natural convection.

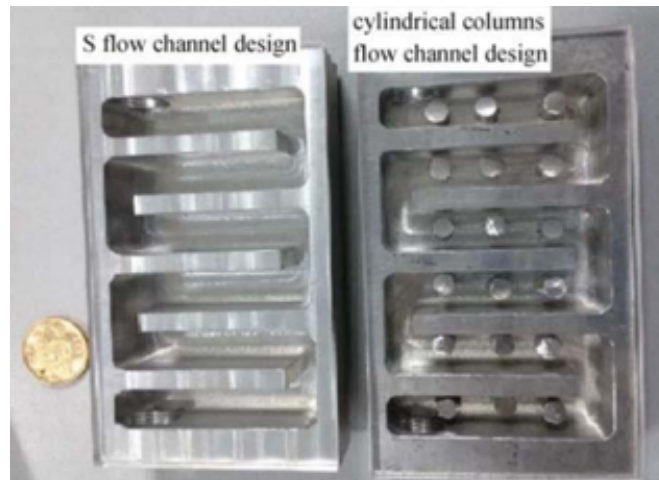


Figure 1.7: S-shape channel with cylindrical channels [51].

In a study by Kan et al, aperture size optimization led to a higher electro-optical conversion in a water-cooling channel. When the output power is 115 W, the laser's thermal resistance is $0.6^{\circ}\text{C}/\text{W}$. However, limited heat flux and an uneven temperature distribution are the drawbacks of this design. Zhao et al [51] proposed a water-cooled channel design with S-shape structure integrating cylindrical rods for turbulence. The structure of the channel design is shown in Figure 1.7. The cylindrical structures in the water channel improved heat dissipation with a thermal resistance of $0.015^{\circ}\text{C}/\text{W}$. These works mentioned till now utilize large area water channels.

With the advent of technology, researchers have been able to fabricate channels on a much smaller scale called micro-channels. The diameter of these channels is usually 10-200 μm with higher surface tension. In 2000, skidmore et al [52] used a microchannel for laser array cooling. The thermal resistance was $0.032^{\circ}\text{C}/\text{W}$ for 10 bar array and at heat flux density of $380\text{W}/\text{cm}^2$, the laser showed good heat transfer. Yet, the issue of non-uniform temperature distribution persisted with single-layer channel. Using a double layer microchannel further improves the heat dissipation and thermal resistance with uniform temperature distribution compared to the single layer microchannel. The improvement in heat dissipation is 6.3% [53]. Leng et al further improved the double layer microchannel design by truncating the top channel and making a stepped heat sink structure. The thermal resistance was further reduced by 30% [54]. In comparison to silicon microchannels, diamond microchannels exhibit superior heat dissipation properties and reduced thermal resistance by 75% [55].

There have been other less versatile methods for cooling laser diodes such as spray cooling [56, 57, 58, 59, 60], jet impingement cooling [61, 62, 63, 64, 65], heat pipe cooling [66, 67, 68], and liquid metal heat dissipation methods [69, 70, 71]. Other than these cooling techniques, heat dissipation in laser diodes is also impacted by mounting of laser diodes. In epi-up packaging, a thick substrate hinders the heat dissipation to the heat-sink resulting in high thermal resistance of LD [72, 73, 74], whereas epi-down packaging consists of active region closer to heat sink. Therefore, the heat dissipation is much better in epi-down assembly compared to epi-up assembly [75, 76, 77, 78]. Figure 1.8 shows the epi up and

epi down assembly of LD.



Figure 1.8: Schematic of (a) epi-up & (b) epi-down mounting.

Heat accumulation in the laser diode cavity can significantly increase the facet temperature by optical absorption, leading to catastrophic optical mirror damage (COMD) which is one of the major limitation in high power semiconductor lasers[79]. In literature, non-absorbing mirrors or NAMs have been used to mitigate the optical absorption [80, 81]. It was shown that the facet temperature decreases as the length of non-injected current window is increased [82, 83]. The drawback of this approach is the high optical absorption and reduction in quantum efficiency although the facet is away from the heat generation region[84]. Recently, Ebadi et al[83] showed the effect of non-injected current window length on the facet temperature profile at 8 A lasing current. As the un-pumped window length increased from $0\mu\text{m}$ to $1500\mu\text{m}$, the facet temperature dropped from 88°C to 62°C . In addition, the laser temperature also increased due to increasing optical absorption. To mitigate this optical absorption, researchers tried to convert the non-injecting current window into a transparent window which does not absorb any optical light and also keeps the facet away from the heat generation region. Arslan et al [85] first demonstrated the facet cooling effect by injecting the separation window making it a transparent window. This 2-section waveguide approach was further studied in detail by Liu and Ebadi [86] showing the optimum length and current for the cooling window. Later, the 2-section waveguide was shown to be COMD free with better performance compared to a standard LD [87].

The problem of high heat load and COBD still persists in high power laser diodes. Pipe et al [88, 89] was the first to propose internal cooling in laser diodes

using band offsets. The band offsets produce thermoelectric coolers near the junction of laser diode. This design's basis was the thermoelectric phenomenon in bipolar devices, which was accomplished by adjusting a SCH laser diode's band offsets [90]. Internal cooling in homojunction diode was further improved by yamashita et al [91] and provided a detailed mechanism for internal cooling. In a study by wang et al [92], graphene has been used as a heat dissipation material to remove the heat directly from the junction of laser diode in an epi-up package. It was shown that $20\mu\text{m}$ thickness of graphene is ideal for efficient heat dissipation from the laser body. At a device output power of 16 W, the temperature difference was around 10K. The improvement in slope efficiency and wavelength characteristics was also observed.

Chapter 2

Design & Simulation

In the previous work, a 2-section approach was utilized in order to separate the window section from the laser section. This approach allowed for reduced temperature at the facet since the heat generation is separated from the facet which in turn helps overcome the COMD behavior. In our current study, we propose a new waveguide design to reduce the temperature and heat load in the bulk of the laser cavity.

2.1 Device Design

The design of the device constitutes of two periodic sections namely the lasing section and the secondary section. The two sections are distributed periodically along the cavity of the laser diode (LD), thus referred to as Distributed waveguide design (DWG). The schematic of the distributed waveguide design is shown in Figure 2.1.

The main idea behind the distributed waveguide design is to reduce the thermal load on the laser cavity. In a standard laser diode, the heat load is uniformly distributed over the waveguide and thus the heat dissipation is limited. The distributed waveguide design, as seen in the Figure 2.1, has periodic sections

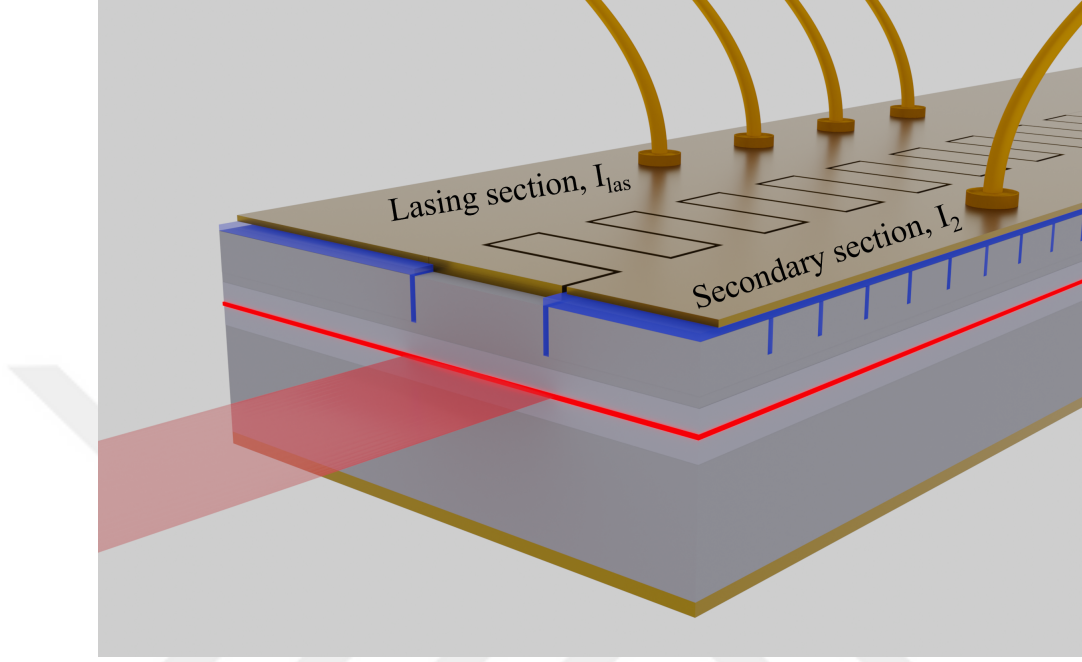


Figure 2.1: Schematic illustration of Distributed waveguide design (DWG).

which are Lasing section and Secondary section. From the previous study of 2 section waveguide design, we understand that different current densities for different regions significantly affects the temperature of the LD cavity. The lasing section is responsible for high output gain, therefore is the main contributor of heat generation in the LD cavity. While the secondary section is to allow the heat from lasing sections to be dissipated more efficiently. To understand the thermal characteristics and identify the optimal device parameters, we analyzed our device by varying two specific parameters:

- Fill Factor (FF):

The ratio of lasing section area to the total area of the device

$$FF = L_{las} / (L_{las} + L_{sec}) \quad (2.1)$$

- Laser length L_{las} :

The length of one lasing section as can be seen in Figure 2.2.

For better understanding and minimizing any additional effects, we performed the study with same active lasing area as a standard LD and while also keeping the lasing section area & secondary section area equal, so the FF becomes 50% from Equation 2.1.

Therefore,

$$L_{las} = L_{sec} = L_{unit} \quad (2.2)$$

With same lasing area of Std. LD and DWG LD, the length of the DWG cavity would be double since half of the DWG cavity area is lasing section and the other half is secondary section for heat dissipation. Fabrication details of the distributed waveguide design are discussed in the next chapter.

2.2 Thermal Simulations

COMSOL Multi-physics software is used for the heat transfer simulations and to show the heat dissipation capacity of the distributed waveguide design. We have utilized two different boundary conditions for the heat transfer as proposed in [93, 94]. The heat sources are set as the quantum well regions of the lasing section as can be seen in Figure 2.2.

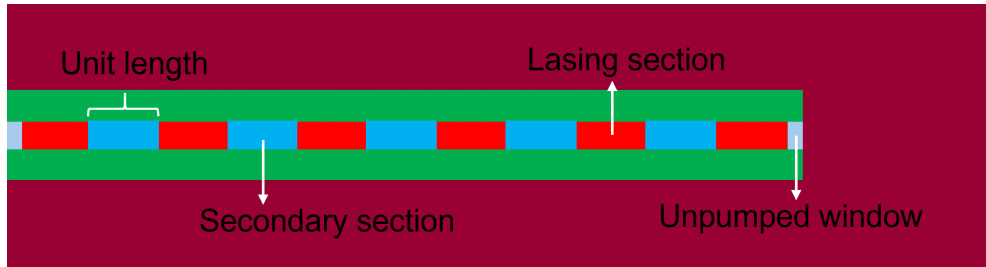


Figure 2.2: Top view of the heat transfer simulation model.

The red regions in Figure 2.2. corresponds to the lasing area and therefore to the heat generation regions and the blue area for the heat dissipation regions. At the ends of the cavity, there are grey regions which are the unpumped regions.

The maximum temperature of the DWG LD for two different heat densities $P_{h.d}$ can be seen for varying unit lengths and compared with the temperature profile of a Std. LD. It can be seen from Figure 2.3. that the peak temperature of DWG reduces with the decreasing unit lengths. It should be noted that the fill factor is 0.5 for this particular case study. When the unit length reaches a value of $5 \mu m$, the temperature profile reaches a uniform state and doesn't alter significantly.

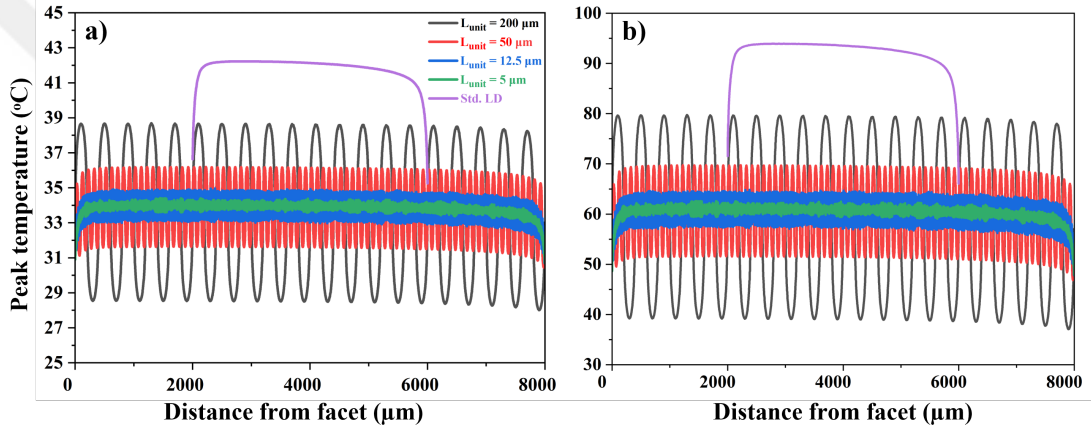


Figure 2.3: Temperature profile comparison for varying unit lengths of DWG with Std. LD when heat density ($P_{h.d}$) is (a) 1 W/mm (b) 4 W/mm.

For heat density $P_{h.d.}$ of 1 W/mm, the difference in temperature profile of a Std. LD and DWG LD of unit length $5 \mu m$ is almost $9^\circ C$ as is shown in Figure 2.3 (a). While the difference becomes significant when the heat density $P_{h.d.}$ reaches a higher level. Figure 2.3 (b) shows temperature profile for heat density $P_{h.d.}$ of 4 W/mm. The peak temperature for a Std. LD is around $93^\circ C$, and it reduces significantly to a value of $62^\circ C$. The difference in max temperature of the LDs is almost $30^\circ C$, which shows that the temperature in the bulk of the cavity reduced around 50%. The heat transfer simulations prove that theoretically it is possible to reduce the temperature and heat load across the bulk of the cavity by half. In addition, the smaller sections in DWG leads to lower and uniform thermal load across the LD cavity.

The peak temperature in the bulk of DWG cavity has been plotted as a function of increasing section length. In Figure 2.4 (a), we can see that the peak temperature is decreasing the smaller and smaller sections for $P_{h.d.}$ of 1 and 4 W/mm. In a quantitative analysis, DWG design works significantly better than a Std. LD at higher $P_{h.d.}$, which is required in high power laser applications. The minimum section length here in heat transfer simulation is $5\mu\text{m}$, taking into account the fabrication limitations of such small patterns.

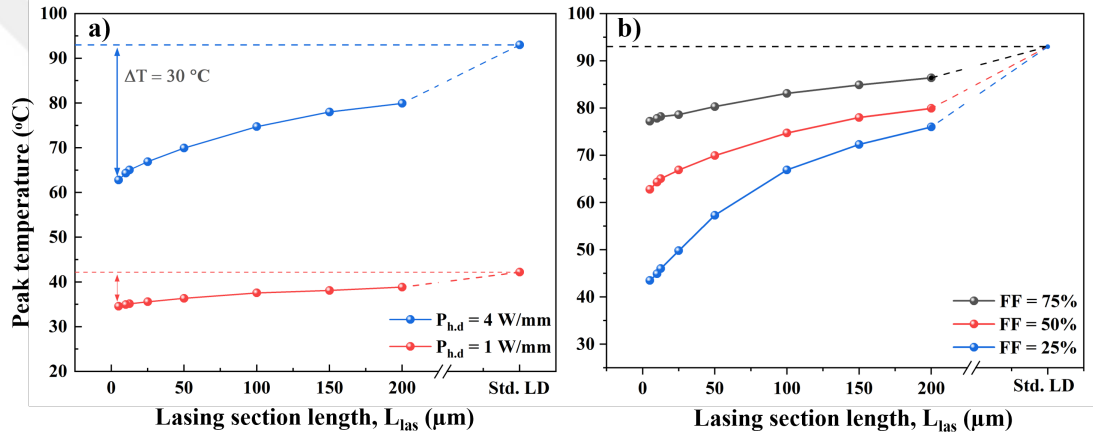


Figure 2.4: Laser section peak temperature in the DWG cavity as a function of varying unit lengths for different (a) heat densities $P_{h.d.}$ (b) Fill Factor.

As we have observed so far, the section/unit length affects the temperature profile of the DWG LD cavity. Fill factor is another parameter that can alter the heat loads in the cavity as is shown in Figure 2.4 (b). This study comprises mainly of DWG LDs with 50% fill factor, however a simple heat transfer simulation has been done to observe the effect of FF on the temperature profile for same lasing section lengths L_{las} . It should be taken into consideration that when fill factor is not 50%, the lasing section length and secondary section length are not equal, which is the case for this particular plot in Figure 2.4 (b). Having a lower fill factor indicates that the lasing area is reduced and the secondary section area is increased. Since lasing area is the heat generation region, the amount of heat generated is also lesser. This is the reason we notice less heat load in 25% fill factor cavity in Figure 2.4 (b). 50% FF cavity compared with 75% & 25% FF cavities, where the total cavity length is same which is 8mm, we notice these differences in temperature profiles. With 8mm cavity length being constant, having more lasing

section, as is the case in 75% FF compared to 50% & 25% FF, the heat generation area is larger, therefore the heat load is larger leading to higher temperature. Same is the case in 25% FF with lower lasing section area which translates to lower thermal loads and a lower temperature profile. Although FF affects the temperature profile in terms of having lower and higher heat generation areas, the temperature of these cavities still decrease with smaller lasing section lengths L_{las} , as heat is still being dissipated through secondary sections.

2.3 Optical Mode Simulation

Anslys Lumerical FDTD software is used to obtain the optimum ridge & DWG depths for the LD cavity. The etch depth for ridge & DWG are calculated separately. First, the optimum etch depth for ridge is calculated and this depth should not confine the optical mode while forming a waveguide. Effective index of the epi structure changes after a certain ridge etch, indicating the confinement of optical mode. Figure 2.5 (a) shows the effective index as a function of ridge etch d_{ridge} and it is clear that there is no change in effective index at d_{ridge} of 700 nm and afterwards, the index starts to decrease pointing towards mode confinement.

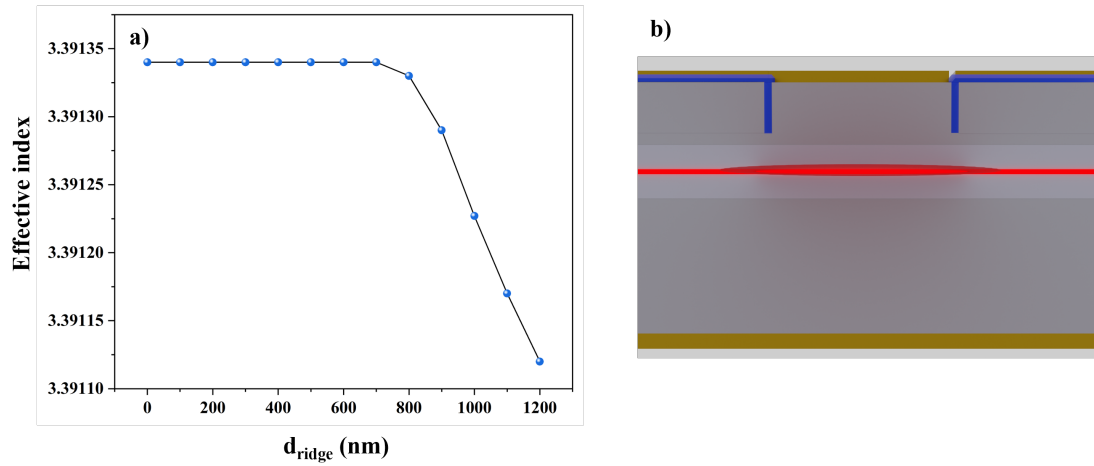


Figure 2.5: (a) Effective index change with respect to ridge etch (b) Front facet of laser diode showing the ridges.

Figure 2.5 (b) shows the front view of the model used in simulation where the blue vertical lines are the ridge etch. The optimum depth for ridge etch is around 600 nm taking into account the fabrication tolerance and avoiding the optical mode confinement. Next, the mode loss is calculated by keeping the ridge etch constant and introducing the DWG separating etch depths.

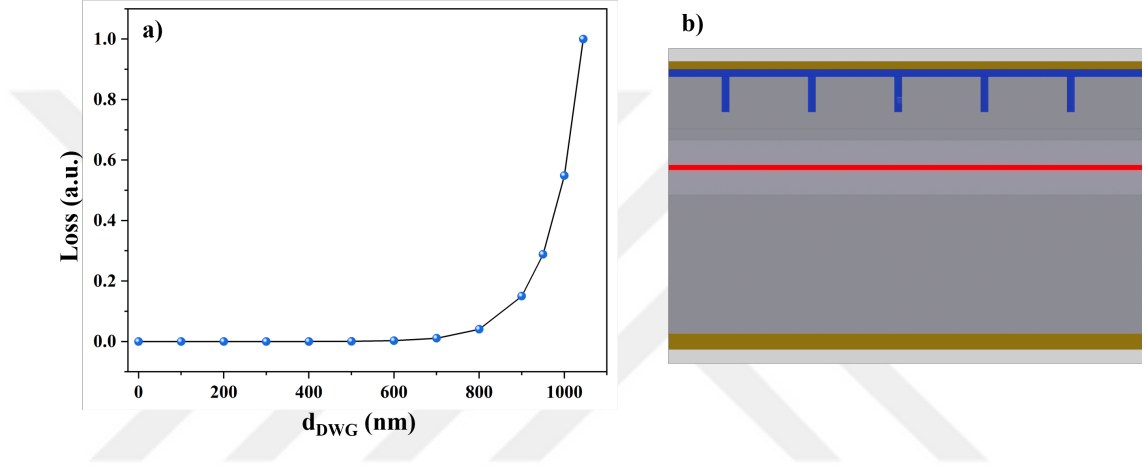


Figure 2.6: (a) Loss introduced in the mode from DWG separation etch (b) side view of the laser diode showing DWG etches.

It can be seen in Figure 2.6 (a) that there is no loss when the d_{DWG} is 600 nm. At 700 nm depth, there is small loss which becomes exponential as the depth increases. Therefore, the optimum etch depth for DWG separations are also taken as 600 nm. Figure 2.6 (b) shows the side view of the simulated model with blue vertical lines are the DWG separation etches.

Chapter 3

Fabrication

A GaAs-based high efficiency epitaxial structure having a single quantum well is used for this study. Each fabrication step must be optimized considering the design parameters of the DWG LD. There are five major steps for DWG LD fabrication. These process steps are illustrated in the Figure 3.1.

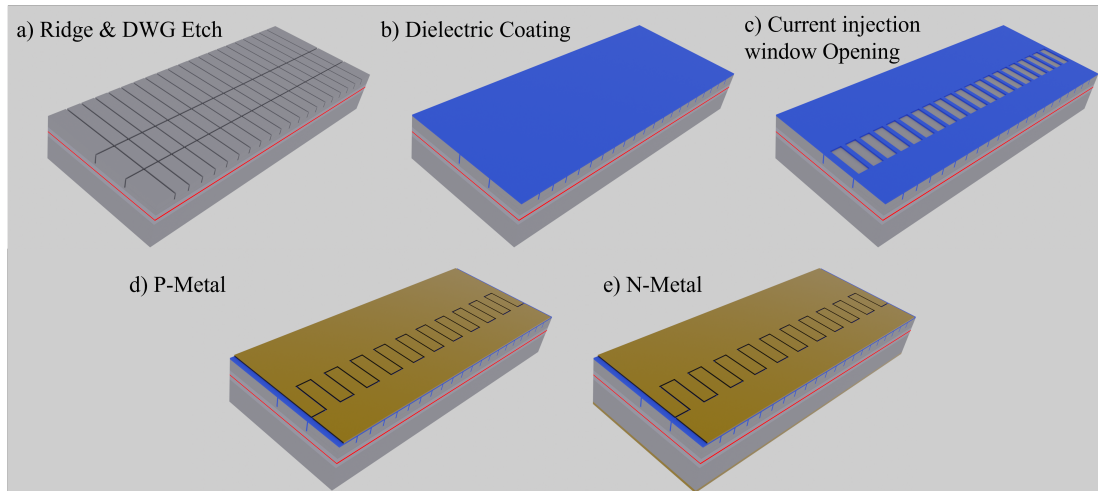


Figure 3.1: Schematic of DWG LD fabrication steps (a) Ridge & DWG etch (b) Dielectric Coating (c) current injection window opening (d) P-metal deposition (e) N-metal deposition.

3.1 Mask Layout

Photolithography is an essential technique in semiconductor device fabrication. Careful design of photomasks are required in this fabrication method, since it is a complex and costly process to manufacture photomask. The mask is required for transferring the patterns using photolithography to the substrate. The substrate is coated with a photoresist and the chrome mask is then aligned for accurate transfer of pattern from the mask to the substrate. UV light is exposed to the photoresist on the mask through the transparent areas in the mask, thus the photoresist undergoes through a chemical change. Afterwards, the exposed regions of photoresist are selectively removed by developing solution for a positive photoresist. Fundamental layout of the mask is shown in Figure 3.2 where the red lines indicate the cleaving regions.

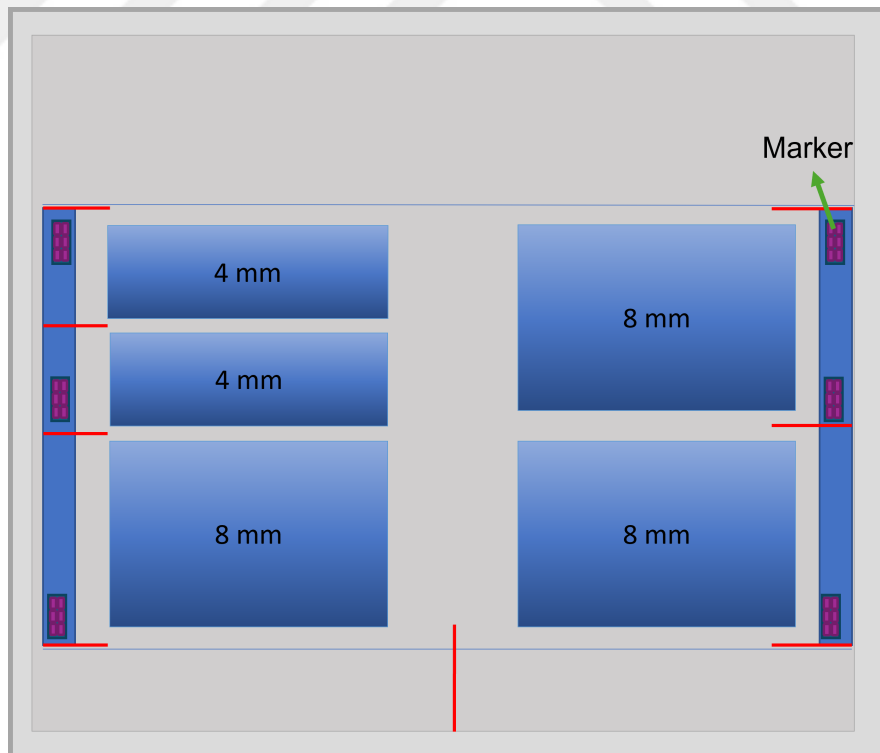


Figure 3.2: General schematic of the mask design.

The mask design constitutes of two 4 mm bars and three 8 mm bars. The 8 mm bars include three different lasing section lengths L_{las} of 50 μm , 25 μm , and 12.5 μm , with fill factor of 50%. These 8 mm long emitters of decreasing L_{las} are designated as D₁, D₂, and D₃, respectively. The 4 mm bars are all standard emitters for comparison. All the emitters in this study are 100 μm in width which is the typical width for a broad area high power laser.

3.2 Process Flow

This section explains the five major fabrication steps for device production.

3.2.1 Cap Layer

Cap Layer etching is the first step in device fabrication. A highly doped GaAs cap layer is present on the top in the epitaxial design. We remove the cap layer from the substrate other than the top of the waveguides. The removal of cap layer is done by wet etching, with a solution of diluted hydrogen peroxide (H_2O_2) and phosphoric acid. The sample is dipped in the chemical solution for 45 seconds, which etches almost 250 nm with etching rate of 330 nm/min.

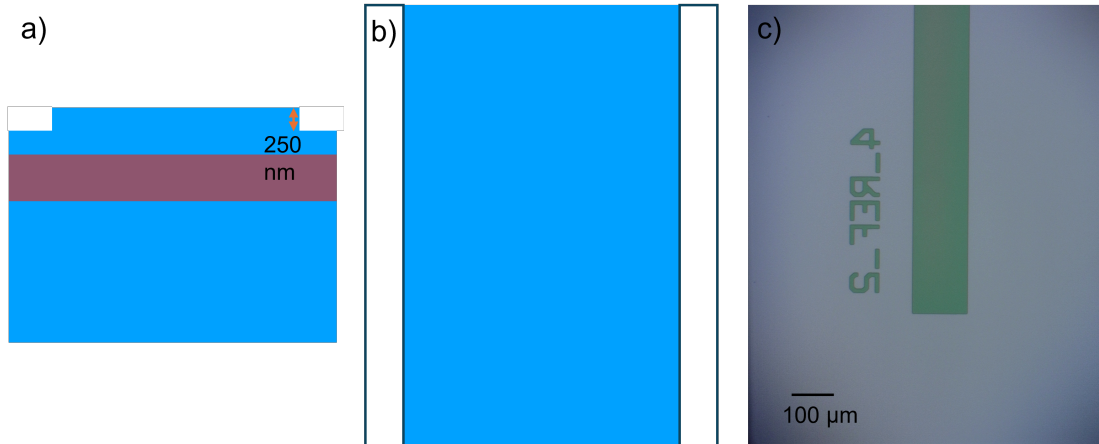


Figure 3.3: Schematic of the (a) cross-section & (b) top view. (c) Optical microscope image (5x) of the top view after the cap layer etch.

Due to the chemical wet etching, the surface of the sample becomes rough which facilitates the adhesion of the dielectric coating in the next steps. As the highly doped cap layer can cause current leakage, removing this layer also protects the facet of the lasers from catastrophic optical mirror damage (COMD).

3.2.2 Ridge & DWG etch

Next step is the generation of a ridge & DWG, which is also done by chemical wet etching through the same etchant solution as in cap layer etch. The purpose of the ridge is to create a refractive index difference with the waveguide having a higher index than the lateral surrounding. This refractive index difference serves as a confinement for optical modes. while the DWG etch serves as an electrical isolator between the two periodic sections. The depth of the ridge & DWG etch is optimized from the refractive index simulations in chapter 2 section 2.3. At this depth of 600 nm, we observe minimum to no optical loss with effective electrical isolation. The width of the DWG separation is almost $3\mu\text{m}$. The schematic and optical microscopic image is shown in Figure 3.4.

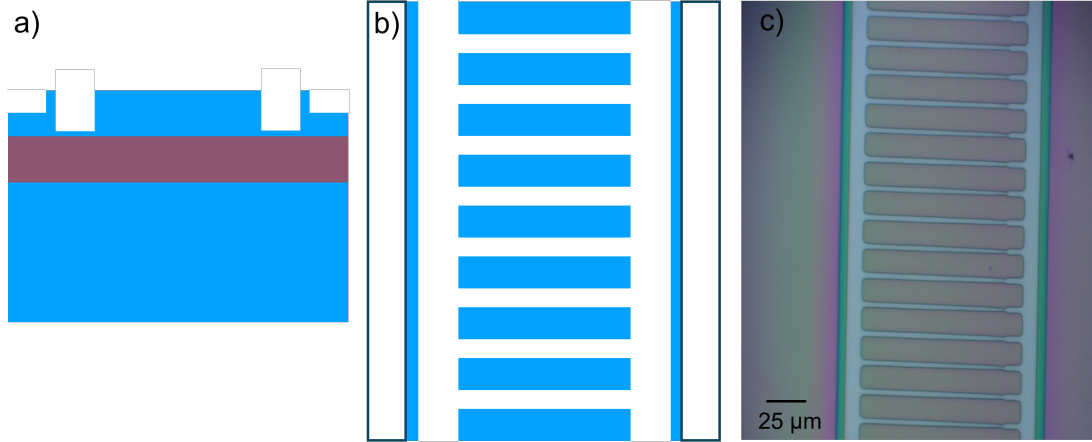


Figure 3.4: Schematic of the (a) cross-section & (b) top view. (c) Optical microscope image of top view with 10x lens after the Ridge & DWG etch.

3.2.3 Current injection window opening

In order to electrically pump only the waveguide region, we deposit a dielectric layer on the sample. The dielectric layer in this case is silicon nitride (Si_3N_4). The dielectric coating also covers the ridge & DWG and after the lithography, the waveguide is opened by selectively etching the dielectric using BOE etchant. As we can see in Figure 3.5, the opened window is inside the periodic section blocks. This step requires very careful alignment in lithography as a little misalignment can result in the removal of dielectric from the ridge & DWG etch areas that can lead to current leakage. The white regions in Figure 3.5 (b) and (c) are the dielectric(nitride) removed regions and from these regions, the current will flow into the waveguide.

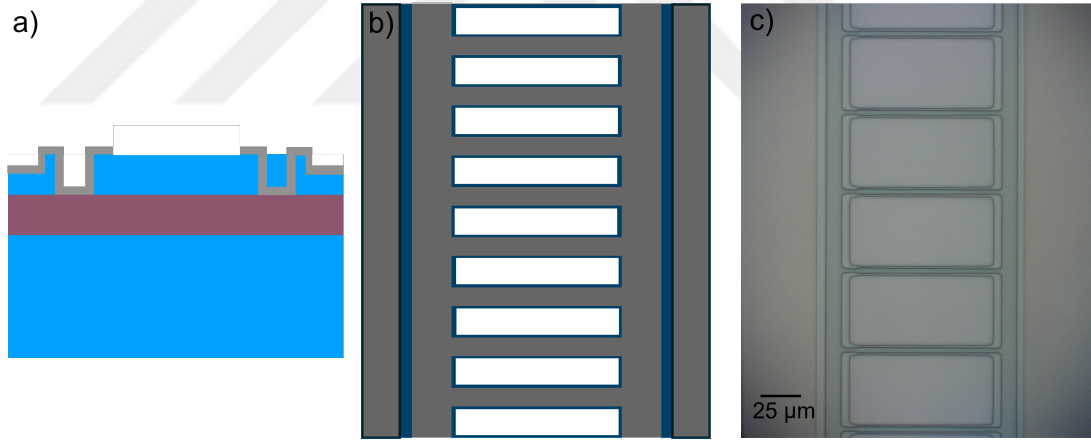


Figure 3.5: Schematic of the (a) cross-section & (b) top view. (c) Optical microscope image of top view with 50x lens, after current injection window opening.

3.2.4 P-Metal deposition

For current injection, we need highly conductive metal layers as both top contact (p-metal) and bottom contact (n-metal). Due to high conductivity of gold (Au), it is a good candidate for top and bottom contacts. However, since the sample is GaAs based, good adhesion is a problem for gold since gold does not stick to the GaAs substrate. To overcome this issue, a thin layer of titanium (Ti) $\sim 20nm$ is deposited on the sample as titanium has very good adhesion with GaAs.

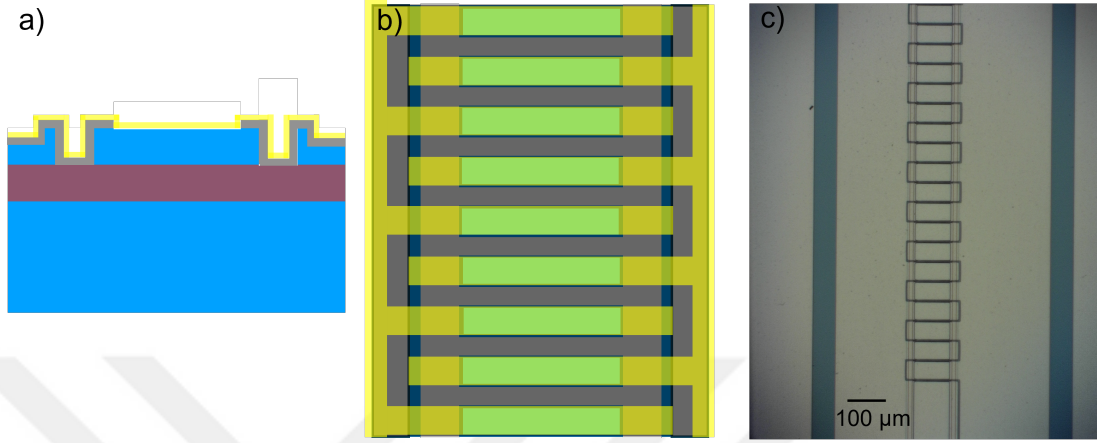


Figure 3.6: Schematic of the (a) cross-section & (b) top view. (c) Optical microscope image of top view with 5x lens, after p-metal deposition and lift-off process.

Other metals than can be deposited on the titanium. Another layer of platinum (Pt) $\sim 20\text{nm}$ is also deposited before gold deposition as platinum works as a diffusion barrier during the final annealing of the sample. Afterwards, gold is deposited on the sample with a thickness of $\sim 100\text{nm}$. Since, the metal is everywhere on the sample, the need to electrically isolate the lasers from each other and also to isolate the lasing & secondary sections arises. To this end, the metal is lifted-off from in-between the sections and the lasers. Image reversal lithography before the metal deposition enables the lift-off process. The alignment in image reversal lithography is also of crucial importance as we need the perfect electrical isolation between the periodic lasing and secondary sections. During the image reversal lithography, the tolerance for misalignment in longitudinal direction is $1\text{ }\mu\text{m}$, which makes it a very difficult and important lithography in the fabrication. The thickness of gold is then increased via electroplating upto $3\text{ }\mu\text{m}$ to ensure uniform current injection.

3.2.5 Isolation & Cleaving

Electrical isolation between the lasers is required for correct optoelectronic measurements of LD. The quantum well is almost $1.5\text{ }\mu\text{m}$ from the top epitaxial layer, so an etch of $2\text{ }\mu\text{m}$ is enough to ensure the electrical isolation of lasers. To achieve

this etch, first the sample is dipped in BOE for 1 minute to remove the dielectric in the trench region and then continued with the same solution as in cap layer etch.

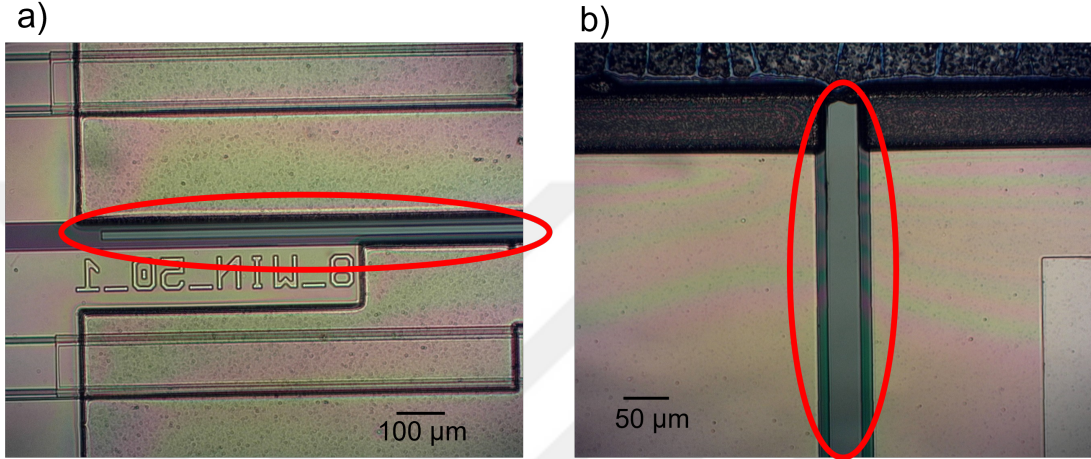


Figure 3.7: Optical microscopic images of (a) isolation etch between lasers (b) cleaving etch.

Cleaving regions are also etched in the same way as isolation areas, removing the dielectric coating and then the etching of GaAs epi layers upto a depth of 10 μm . The etching in cleaving areas provide the diamond tip for cleaving direction.

3.2.6 N-metal contact & Annealing

At the end of fabrication, bottom contact is made on the back side of sample. A 20nm layer of Ge is deposited before the deposition of 100nm gold. Rapid thermal annealing is done afterwards for diffusion of Ge in to the substrate, which reduces the contact resistance.

Chapter 4

Results & Discussion

As mentioned in Chapter 3, we have explored three DWG LD designs with $L_{las} = 50, 25, \& 12.5 \mu\text{m}$ for the thermal and electro-optical characteristics.

4.1 Resistance measurement

Since we have 12 laser diodes on a single bar, the first step in measurements is to check the resistance between the lasers. One of the probes goes on one LD and the second probe goes to the immediate next LD. The current-voltage (IV) characteristics can be seen in Figure 4.2.

The current reaches the maximum value of 0.1 mA at a voltage of 64 mV, which corresponds to the resistance of 640Ω between two consecutive LDs. Therefore, the $2\mu\text{m}$ etch depth in trenches is enough for electrical isolation of the emitters.

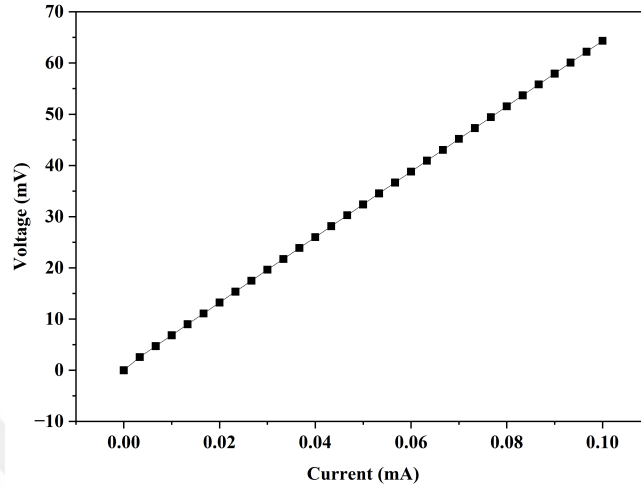


Figure 4.1: Current-Voltage characteristic between two consecutive laser diodes.

4.2 Calibration

After ensuring the electrical isolation between the lasers, the optical measurement setup was calibrated via an industrial laser.

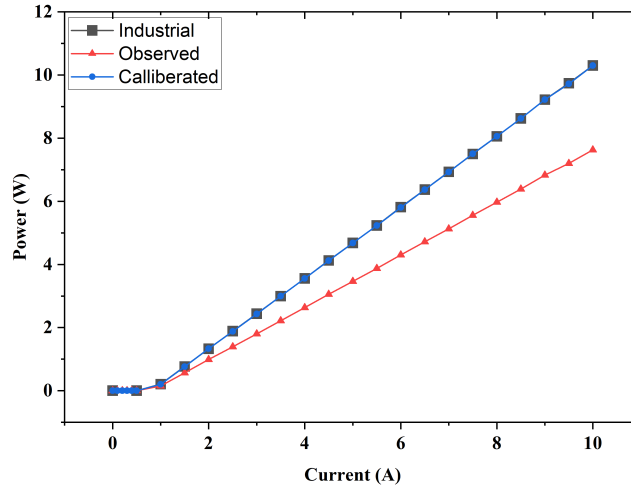


Figure 4.2: Calibration of optical output power.

We measured L-I from the industrial laser diode and matched it with the data from industrial data sheet. Figure 4.1 shows the measured optical power compared to the data sheet. It should be noted that the LI measurement was

done on the same LD. The observed LI curve (red dots and line) showed the slope which was low by a factor of 1.35. Therefore, the calibration factor came out to be 1.35, which was confirmed by L-I measurements on different other industrial lasers.

4.3 Optical & Electrical performance

The measurements were performed at 25°C for all the emitters. As an initial test, the output optical power of DWG LDs was measured. The DWG LDs were investigated for their output power and slope efficiency as a function of secondary current I_2 , as shown in Figure 4.3. The CW L-I data measured for DWG LDs D1, D2, & D3 in Figure 4.3 [(a), (b), and (c)] show that the output optical power increases with increasing secondary current I_2 and the effect of increasing I_2 is shown as a function of slope efficiency in Figure 4.3 (d) for three designs of DWG.

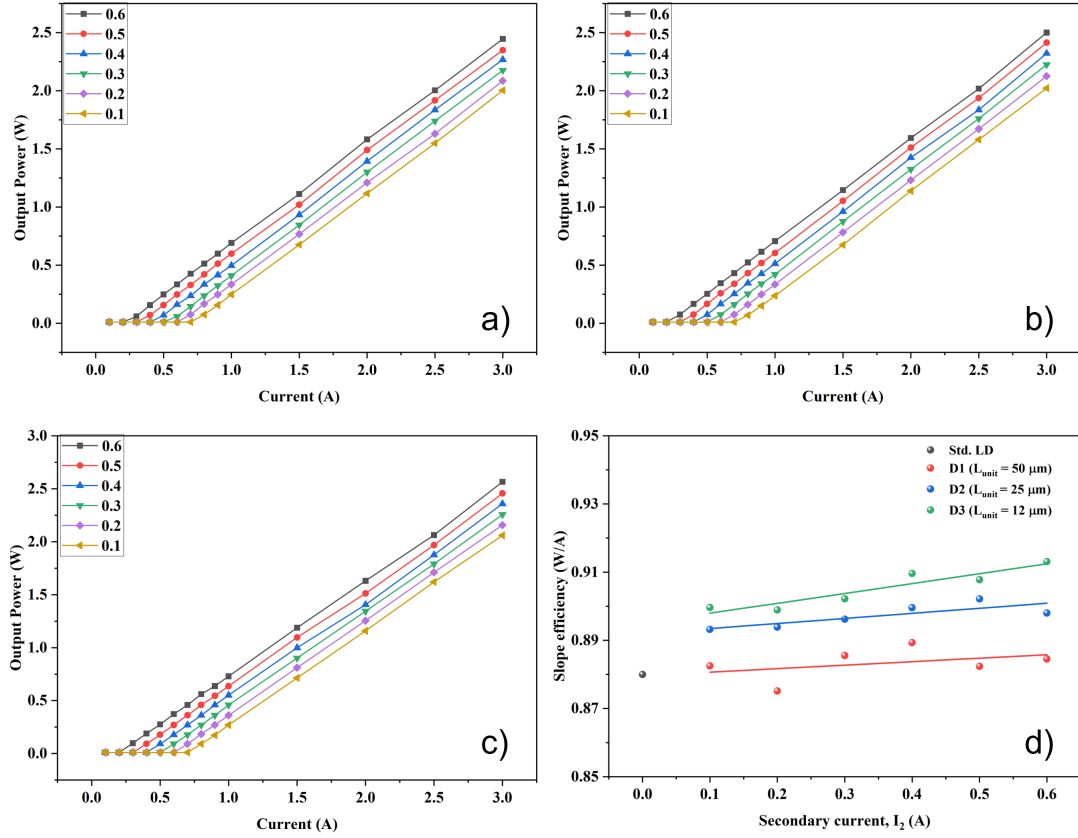


Figure 4.3: Output optical power under CW operation at 25°C with varying I_2 for (a) D1 (b) D2 (c) D3. (d) slope efficiency vs. secondary current I_2 .

Since DWG LDs D1, D2, & D3 corresponds to the decreasing section length $L_{unit} = 50, 25, \& 12 \mu m$ respectively, we can deduce two major points from the plot (d) in Figure 4.3.

- The slope efficiency is increased as the section lengths L_{unit} get smaller, for all values of secondary current I_2 .

$$D3_{slope} > D2_{slope} > D1_{slope} \quad (4.1)$$

We can also see that the slope efficiency of the Std. LD is in the same range as D1. This increase in slope efficiency for D2 & D3 can be attributed to the effective heat dissipation in these designs.

- The slope efficiency increases as the secondary current I_2 also increases.

The secondary current I_2 cannot be increased more than 0.6 A, since the total length of the secondary section is 4 mm, and for a standard LD of length 4 mm, the lasing threshold is 0.6 A. Therefore, the injected current for the secondary section should be less than the lasing threshold of std. LD. Thus, the output optical power would come only from the lasing sections of the DWG. Additionally, the heat generation in secondary sections L_2 should also be minimum as I_2 makes the secondary sections optically transparent without lasing.

For further testing, we focused on the best-performing DWG LDs with secondary current $I_2 = 0.5A$. The facet of the laser diodes was not passivated, which limits the amount of current injection in the lasing section to avoid damaging the LDs. In Figure 4.4, the output optical power is shown for three designs of DWG compared with std. LD as a function of lasing current I_{las} , at $I_2 = 0.5A$.

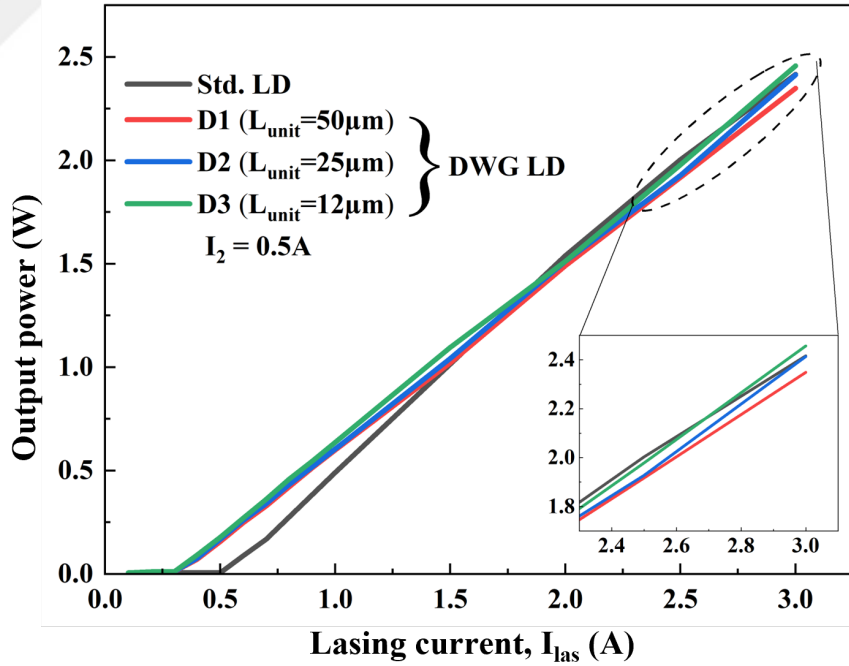


Figure 4.4: Effect of L_{unit} on the output power of the DWG LDs compared with std. LD at $I_2 = 0.5A$.

The threshold of DWG LDs is 0.3 A while for the std. LD, it is 0.5 A. This lower threshold could be due to the reduced heat load on DWG LDs as the heat dissipation is much better compared to std. LD, as is shown by the heat transfer

simulations in Chapter 2. Another factor that can reduce the I_{th} in this particular case is the current leakage from the secondary section. The output power of a LD is characterized by the slope efficiency and it is clear in Figure 4.4 that the slope of std. LD is higher than the three designs of DWG upto $I_{las} = 2$ A. After $I_{las} = 2$ A, the slope of std. LD starts to decrease while the DWG LDs maintain their slope efficiency which could indicate the reliability of DWG LDs over a std. LD. The inset of Figure 4.4 shows output power with I_{las} 2.3 - 3 A. The slope efficiency in Figure 4.3 (d) for std. LD is taken from the inset of Figure 4.4. It can be observed that D3 shows the highest slope (0.91 W/A), while the slope of D2 (0.89 W/A) is a bit lower than the slope of D3 and D1 has the lowest slope (0.88 W/A) in DWG designs. The higher slope of D3 and D2 compared to D1 and std. LD could be due to the better heat dissipation from smaller sections of D3 & D2. As there would be less heat load on the device, the conversion efficiency will increase which is shown in Figure 4.5 (b). The IV characteristics and PCE of the LDs are shown in Figure 4.5.

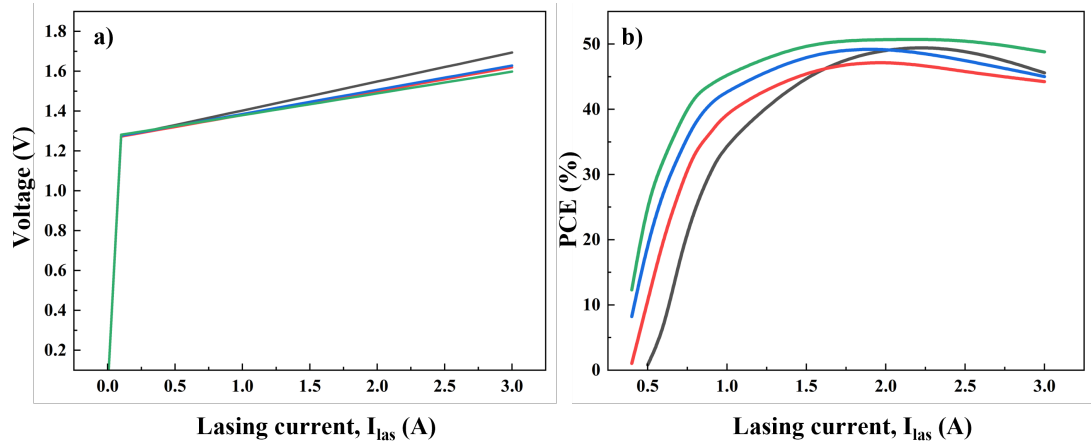


Figure 4.5: Comparison of std. LD & DWG LDs (a) I-V characteristics (b) power conversion efficiency.

The voltage of std. LD is higher than DWG LDs where D1 & D2 are almost same while D3 has the lowest voltage. Since voltage represents the vertical resistance of the LD, it is positive to consider that having a lower voltage indicates a lower input power. Using the LIV data, the power conversion efficiency (PCE) of the LDs is calculated, where DWG LDs show a trend of increasing PCE with the decrease in L_{unit} . Therefore, D3 showing the highest PCE can also indicate

improved heat dissipation leading to lower bulk temperature and so the efficiency of the LD improves. As we see in Figure 4.5 (b), the std. LD has the highest PCE at 2 A and then it starts to decrease which indicates the deterioration of the LD cavity. As mentioned before, these measurements are taken at heat sink temperature of 25 °C & at an I_2 of 0.5 A. When the secondary current I_2 is zero, the heat transfer would occur in the following two ways.

- The heat generated in the lasing section will be dissipated through the secondary sections as depicted in the heat transfer simulations.
- Since the secondary section is not pumped ($I_2 = 0A$), these sections will not be optically transparent anymore and instead will absorb the laser light within the cavity.

Thus, the output of the LD will be decreased and there will be extra heat generation from the absorbance of laser light.

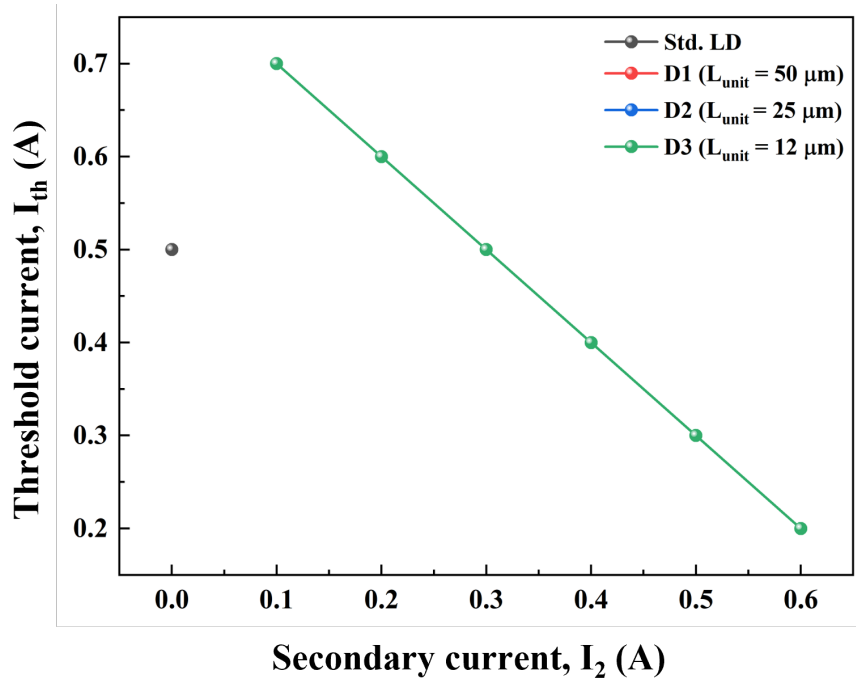


Figure 4.6: Variation in I_{th} as a function of I_2 .

The threshold current I_{th} is plotted against secondary current I_2 for DWG and std. LD in Figure 4.6. The data points for D1, D2, and D3 are shown by red, blue, and green dots & line respectively, which are overlapping in Figure 4.6. As we can see the threshold current decreases as the current to secondary sections is increased. This indicates that the total lasing area of D1, D2, & D3 is the same and these devices differ only in terms of their unit length L_{unit} . Since the lasing area is same for DWG LDs, we can safely assume that the improvement in output power and PCE for D3 as compared to D1, D2, and std. LD, shown in Figure 4.4 & 4.5 (b) is due to lower temperature of the LD cavity enabled by smaller sections of DWG. To actually prove the lower temperature of DWG cavities, we need a more reliable method which is the wavelength shift method.

4.4 Wavelength shift

One of the most reliable methods to verify the internal temperature of a LD is the wavelength shift method. The wavelength shift method depends on the waste power P_{waste} generated by the LD. Waste power or P_{waste} is the amount of electrical energy that is not converted into optical energy but instead is converted to heat energy, shown by the equation.

$$P_{waste} = P_{in} - P_{out} \quad (4.2)$$

Thus, the waste power converted to heat energy raises the temperature of the cavity and since the temperature of a LD cavity is associated with the bandgap and refractive index. A rise in temperature will cause the bandgap to shrink and as we already know that the wavelength of output beam depends on the bandgap, any change in the bandgap will cause the wavelength to shift. Figure 4.7 (a) shows the wavelength change with respect to the lasing current I_{las} .

As the lasing current is increased, heat will be generated in the active region, raising the temperature of the active region and thus a redshift can be observed

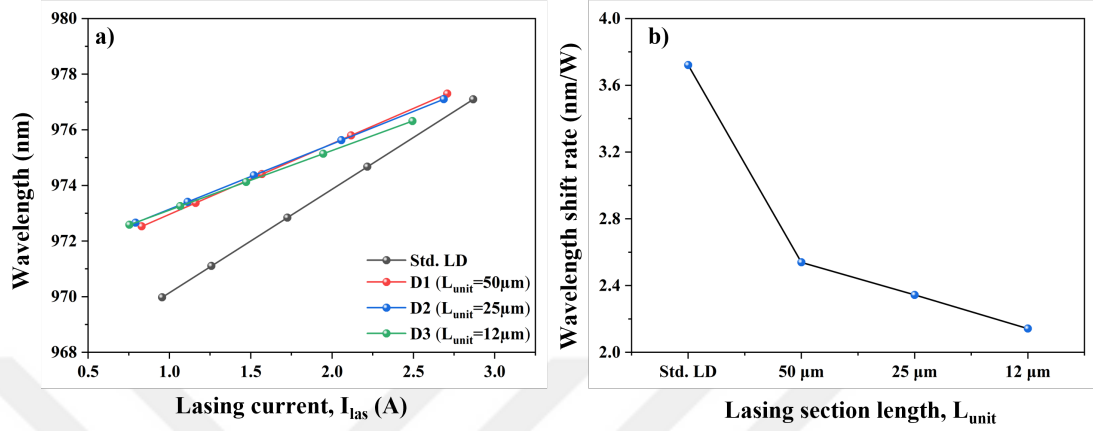


Figure 4.7: comparison of wavelength shift rate for different LD design.

in the spectrum. For each lasing current, multiple data points were taken for reliability of the spectrum measurements. These multiple data points were then averaged. As we can see from the Figure 4.7 (a), the slope of wavelength shift for the std. LD is higher than all the DWG LDs, it is sufficient proof that the temperature of std. LD is higher than the DWG LDs. In essence, the novel DWG design points toward a reduced temperature of the LD cavity and better heat dissipation. In terms of section length L_{unit} , it is evident that D1 shows higher slope in wavelength shift and D2 design has a little lower slope. While the D3 design which has the smallest section length of $L_{unit} = 12.5 \mu m$, shows the lowest slope among DWG designs. Wavelength shift rate is shown for three designs of DWG and compared with std. LD in Figure 4.7 (b). As we decrease the section length L_{unit} , heat dissipation becomes better and results in lower body temperature which is also evident from heat transfer simulations in Chapter 2.

Chapter 5

Conclusion

In conclusion, we have resolved the constraint of conventional cavity length for HPLDs and experimentally shown the possibility of extended cavity length. The introduction of a distributed waveguide design in laser diodes represents an innovative approach to enhance heat dissipation throughout the laser diode, hence reducing the thermal load on the device. The distributed waveguide design consists of two periodic sections for lasing and transparency. We developed a 3D heat transfer model to study the heat dissipation in the DWG design and compared with a standard LD. The simulation results indicate a significant reduction in the internal temperature of the laser diode cavity. In addition, the length of the periodic sections significantly affects the internal temperature of the LD. This design facilitates a decrease in junction temperature and enables the acquisition of longer optical cavities. Experimentally, the output power and power conversion efficiency of DWG is better than a std. LD. The wavelength shift of DWG LD points toward lower active region temperature compared to std. LD. The experimental data are consistent with the heat transfer simulations. Optical mode simulations have been done to optimize the ridge and DWG separation etch depths. Enhanced thermal dissipation in DWG increases output power, voltage, and conversion efficiency. Smaller sections enhance heat dissipation and hence lowering the internal temperature, as evidenced by the slope of the wavelength shift. This study enables the investigation of the integration of DWG design with

a two-section methodology. Exploring single current injection for distributed waveguide design would be quite beneficial as it will allow a significant enhancement in the device's longevity and consistent output power with an epi-down assembly.



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