1. Introduction

All scientific and technological progress throughout the history of humanity can be traced back to two fundamental principles; curiosity and courage in exploring the unknown. From the time when the first humans observed fire and, in contrast to their initial reaction of fleeing, instead demonstrated curiosity and attempted to control this element. To the present day, where millions of individuals are engaged in daily efforts to identify solutions to numerous unanswered questions, these two principles continue to serve as the foundation for our collective advancement. This thesis presents a further courageous attempt to identify unknown aspects and to contribute to the advancement of laser development. The primary objective of this study is to investigate and develop new methods to enhance the capabilities of semiconductor/diode lasers in wavelengths where they are currently constrained and to create compact devices that can be easily accessed for future applications.

1.1 Motivation

The initial question that may be posed by the reader is why semiconductor lasers have been selected for this study. The answer to this question can be provided at this point, as semiconductor lasers have been established and widely used in many applications since their first creation by R. N. Hall, G. E. Fenner, J. D. Kingsley, T. J. Soltys, and R. O. Carlson in 1962 [1,2]. The compactness, robustness, and low cost of semiconductor lasers have made them a perfect fit for a wide variety of applications, including biomedicine, fiber optic telecommunications, optical drivers, industrial 3D laser welding, airplane wing sensors, and numerous other fields [3,4]. The small size of the chips enables their integration into matchbox-sized modules, which in turn allows for the creation of more complex laser systems. These include master oscillator power amplifiers (MOPAs), spatial and polarization multiplexing modules, and nonlinear wavelength conversion modules. [5–7]. Laser modules based on laser diodes play a pivotal role in applications where space is limited and the environment is harsh, such as in space and in nuclear fusion [8,9]. Cube nanosatellites have a volume of only 1000 cm^3 and masses from 1 to 10 kg, and compact ECDL-MOPA laser modules with a footprint of only 80 x 30 mm^2 have already been realized to be used in them for an iodine-based optical reference [10].

The second question is to identify the wavelengths at which laser diode (LD) emission must be improved and the reasons for this. The first wavelength examined in this thesis is in the near-infrared emission around 761 nm. These wavelengths are useful for several applications, but only a few compact devices are available. Tunable distributed feedback (DFB) lasers emitting around 760 nm with a long lifetime have been developed for sensing and spectroscopy applications [11,12]. A DFB laser has been employed for the precise determination of the air mass along the line of sight from ground or space-borne atmospheric spectra of the oxygen A-band near 760 nm using a ring cavity down spectrometer [13]. In the field of metrology, an interferometer with a DFB laser has been developed for length measurement with an impressive resolution of a few nanometers [14]. In dermatology, laser modules are utilized for hair removal with laser bars of high optical power, contributing to both the medical and industrial sectors [15]. The majority of the applications require compact devices with high optical power and good beam quality. In recent years, single emitters with high brightness have been developed at wavelengths close to 760 nm. Distributed Bragg reflector (DBR) tapered lasers have been fabricated at 783 nm and 785 nm with high optical powers up to 7 W [16,17]. However, single emitters are limited in optical power due to the risk of catastrophic optical mirror damage (COMD) and are unable to scale up optical power indefinitely.

An additional indirect yet significant application of the 761 nm single-longitudinal mode (SLM) emission is its use as a seed laser for the generation of other wavelengths via nonlinear processes. The second harmonic of the 761 nm is the 380.5 nm, while the sum frequency of these two wavelengths results in emission at the UVC wavelength of 253.7 nm. Although LDs have high optical powers with good beam quality in the visible and IR spectrum [18], their capabilities in the UV spectrum are however very limited. The UV spectrum (400-200 nm) is a part of the electromagnetic spectrum with many applications in many fields such as spectroscopy, sensors, optical communications and biotechnology. Specifically, in the UVA region (400-315 nm), a non-line-of-sight optical communications link has been developed, which has been appropriately enhanced by the use of a ridge waveguide laser diode at 375 nm. This enables high data rate underwater wireless communications [19]. In the field of biotechnology, the excitation of fluorophores and the use of flow cytometry have been demonstrated using a laser diode at 375 nm, which allows for the low-cost and high-throughput analysis of cell populations [20]. In the UVB range (315-280 nm), phototherapy is employed to treat life-threatening skin diseases such as vitiligo and psoriasis [21,22]. Furthermore, UVB light is used to enhance the production of metabolites in vegetables that confer a number of health benefits to the consumer, or to control the morphology and shape of flowers [23]. The UVC spectral band (280-100 nm) is utilized in a variety of applications, including water treatment, sterilization of medical equipment, and the detection of a diverse range of gases and biomolecules [24]. In particular, the emission at 253.7 nm can be employed for spectral analysis and the detection of phosgene ($COCl_2$) and mercury (Hg). Phosgene is a highly toxic gas that was used as a weapon during World War I and is now used in industry to produce high-quality paints and plastics [25–27]. Mercury (Hg) is the only pollutant that exists as a free atom in the lower levels of the atmosphere, with concentrations varying between 1.0 and 1.7 ng m^{-3} [28]. The majority of atmospheric emissions of mercury are primarily attributable to anthropogenic sources, including artisanal and mining activities, combustion engines, and other human-made processes. These chemical compounds are highly toxic and classified as neurotoxins, necessitating prompt and accurate detection [29,30]. A laser diode-based spectrometer at this wavelength could be implemented for low absorption measurements using modulation techniques, which offer higher sensitivity compared to direct absorption [31,32]. Another potential application is through the use of $6^2P_{1/2} \rightarrow 6^2S_{1/2}$ atomic emission of Hg, which necessitates the use of UV light for excitation. It has been proposed for the optical cycle of atomic clocks [33,34]. The ionized Hg clock operates at a very high frequency (40.5073 GHz) in comparison to other ion clocks, which renders it immune to ambient magnetic fields [35,36]. The Jet Propulsion Laboratory has developed a space-qualified Hg+ clock, known as the Deep Space Clock (DSC), which was launched into low Earth orbit by NASA in 2019 for the purposes of space navigation and radio science [37].

1.2 Approaches

The third and most significant question addressed in this dissertation is how to enhance laser emission in the UVC spectral band. The direct laser diode emission in the UVC band has not yet been successfully achieved due to the high defect density of nitride III materials and the presence of optical polarization crossover in conventional AlGaN-based quantum wells. Although progress has been made in light-emitting diodes (LEDs) at higher UV wavelengths, the efficiency of these chips for laser emission remains limited [38]. One potential solution to this issue is the use of nonlinear conversion. In this approach, high-power LDs can be utilized at higher wavelengths, and a nonlinear crystal can be seeded for second harmonic generation (SHG) or sum frequency generation (SFG) to emit light at a lower wavelength. In such a case, the generated UV optical power is limited only by the optical power of the seed laser.

The objective of this research is to generate UVC emission in a single longitudinal mode (SLM) at 253.7 nm with the highest possible optical power and to attempt to miniaturize a portion of this process. This objective is accomplished by initially utilizing an SLM laser diode emitting at 761.1 nm, subsequently passing a second harmonic crystal to generate emission at 380.55 nm, and finally passing both wavelengths to a nonlinear sum frequency generation (SFG) crystal to emit the final wavelength of 253.7 nm. The first challenge of this work is to build high radiance laser source at 761.1 nm. Previously, single emitter diodes have been fabricated near 760 nm, at 783 and 785 nm, with distributed Bragg reflector (DBR) tapered lasers and with high optical powers up to 7 W. However, the emission at 761 nm is still in its nascent stages, with lower electro-optical efficiency and the optical power of the single emitters limited to a few watts [16,17]. Another significant limitation on the optical power of single emitters is the COMD. When the pump current to a semiconductor laser exceeds its power density, light absorption and temperature build-up occur, leading to the destruction of the material at the laser facet [39]. A useful method to overcome this obstacle and further increase the optical power is Coherent Beam Combining (CBC). In this method, two or more beams can be coherently combined into a single beam, resulting in a linear increase in the total optical power of the combined beam while maintaining beam quality. This technique is the optimal option when combining beams from tapered amplifiers because it cleans up the spatial profile and improves the beam quality of the combined beam [40].

In the recent past, the CBC method at 1064 nm has demonstrated remarkable results. In one experiment, 47 elements of a semiconductor optical amplifier array were coherently combined with a diffractive optical element, achieving optical powers of up to 40 W with very good beam quality and a combining efficiency of 87% [41]. Single emitter LDs have also been coherently combined into a single beam, and these experiments have shown very good results at different wavelengths. A CBC system that combines two tapered amplifiers with a high combining efficiency of 81% in pulsed operation at 828 nm has been implemented for direct detection in water vapor differential absorption lidars [42]. At 976 nm, SLM continuous wave (CW) emission with an optical power of up to 12.9 W was generated by coherently combining three individually amplified beams with a combining efficiency of more than 65% [43].

Furthermore, SLM quasi-continuous operation with an optical power of up to 22.7 W was generated by coherently combining four amplified beams with a combining efficiency of more than 64% [44]. The coherent combination of single-emitter tapered amplified beams allows this concept to be miniaturized into a compact laser module, due to the straightforward and cost-effective integration of micro-optics.

In the initial phase of the experiments presented in this dissertation, a macroscopic tabletop CBC setup and its subsequent miniaturization into the first compact laser module with dimensions of 76 x 43 x 15 mm^3, which implements the CBC method, is demonstrated. In the second part of the experiments, the previously developed CBC laser module is employed as a pump source in a periodically poled $MgO:LiTaO_3$ circular waveguide crystal for SHG, resulting in the generation of laser emission at 380.55 nm. In the final stage of the experiments, both beams were used in a periodically poled $LaBGeO_5$ bulk crystal, which generated the desired emission at 253.7 nm via sum frequency generation. All experimental setups and the challenges are fully discussed, and several calculations have been performed to facilitate the process and to enhance comprehension of the underlying science. The following chapter presents the theoretical framework that is essential to the study.