Tunable Diode Lasers (TDL) for Spectroscopy and Environmental Monitoring

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ABSTRACT

The current status of III-V tunable diode lasers (TDLs) emitting between 1 -5pm wavelengths for spectroscopy and chemical analysis is described. Single mode distributed feedback (DFB) strained layer InGaAs(P) lasers grown on InP substrates with emission wavelength from 1.2 to 2.06 μm have been developed at JPL. DFB ridge waveguide lasers at 2,06pm have operated continuous wave (CW) up to 50°C with output power of more than 10 mW and excellent reliability. Space qualified tunable diode lasers have been developed for planetary atmospheric studies for the first time. TDLs at the wavelengths of 1.37 μm, 1.43 μm, and 2.04 μm for the detection of water, carbon dioxide and their isotopes have been fabricated for implementation in the Mars Volatiles and Climate Surveyor (MVACS) instrument as part of Mars '98 flight. The performance of antimonide-based quantum well lasers emitting in the 2 to 5 μm has improved significantly in recent years. Pulsed performance at temperatures over 200"K and CW performance over 150"K has been reported at wavelengths over 3 μm by several laboratories, Further reduction of the non-radiative Auger recombination to improve the CW operation of the antimonide-based lasers at higher temperatures is currently under investigation by several groups.

INTRODUCTION

Many Molecular species have absorption bands in the 1-5 μm wavelength region where II I-V diode lasers can operate. Single frequency diode lasers can be temperature or current tuned so that an output wavelength coincident with a specific gas-absorption line can be obtained. Detection techniques based on the modulation of laser current yield sensitivities for measuring one part per million absorbance or smaller. For many gases this sensitivity corresponds to detection of sub-parts-per-million (ppm) concentrations over path lengths of few meters [1]. Compatibility with fiberoptic makes this technique attractive for certain remote-sensing applications, where a single laser source might probe gas concentrations in different locations accessed by fiberoptic [2]. Their sensitivity, speed, and ability to quickly discriminate gases makes them ideal for life support applications in the Space Shuttle and for the Space Station. Unlike the mass spectrometers and gas chromatography that are usually employed in these applications, TDLs require no pumps or other moving parts and are much less susceptible to poisoning by reactive gases (hydrocarbons, sulfur gases, acids). They should therefore provide enhanced reliability as well as lower mass and power consumption.

Based on their material system, semiconductor lasers can be divided in to two main groups of IV-VI (lead-salt) and III-V lasers. Lead-salt lasers with emission wavelengths in the 3 to 30 μm wavelength range have been widely used for spectroscopy applications. Though the lead-salt lasers can easily be tuned over a relatively large wavelength range by temperature or current tuning, temperatures far below 150"K are required for CW operation and the longer the emission wavelength of the laser the lower the operating temperature. Besides the low temperature requirement, the major problem with lead-salt lasers is their reliability due to poor quality of IV-VI epitaxial material and difficulty in device fabrication. In contrast to lead-salt lasers, III-V InGaAsP/InP lasers operate in the 1.1-2.1 μm wavelength range at room temperature with excellent performance and reliability. With their sensitivity, low power consumption, low mass, and compact size, instruments based on these near-infrared TDLs have been developed for numerous commercial applications. They are used in toxic gas monitoring (workplace detection or industrial site monitoring), for medical applications such as breath analysis, mine safety monitors (methane and carbon monoxide detection), monitoring of pollutants in stack gases, and on-line monitors of combustion or chemical processes.

Considerable progress has also been made in the mid-IR semiconductor lasers based on III-V antimonide material system [3-10], New types of lasers have been demonstrated, output power has been substantially increased and operating temperature has been extended, We describe in this paper the current status of III-V based semiconductor lasers in the 1-5 μm wavelength range. Single mode distributed feedback (DFB) strained layer InGaAs(P) lasers grown on InP substrates with emission wavelength from 1.2 to 1.65 μm is described in section II. InGaAs/In P strained quantum well lasers have been used for emission in the 1.65-2.1 μm wavelength range which is described in section III. The status of mid-I R semiconductor lasers is reviewed in section IV with several applications of tunable diode lasers described in section V.

INGAASP/INP QUANTUM WELL LASERS IN THE 1.1-1.65 μM RANGE

The mature technology of near-IR 1.3 and 1.55 μm InGaAsP/InP diode lasers for fiberoptic communication has been extended to fabricate lasers that emit anywhere in the wavelength range of 1.1- 1.7 μm. The typical lasers developed are strained-layer multi-quantum well (MQW) structures epitaxially grown on InP substrates. In such lasers, simple resonators formed by cleaved facets on the ends of the laser cavity often allows oscillation in multiple longitudinal modes covering 2-5 nm wide spectral range and thus is not suitable for spectroscopy applications. Spectroscopic applications typically require single wavelength operation with some degree of tunability. Highly-stable single-longitudinal-mode operation may be met by a distributed feedback (DFB) or distributed Bragg reflector (DBR) laser cavity. Both types of devices require the incorporation of a submicron lithographically defined grating buried within the laser structure which is accomplished using state-of-the-art fabrication and epitaxial techniques. Even though single mode lasers at 1.3 and 1.55 μm wavelength have been commercially available for many years, the availability of single-mode lasers at specific wavelengths suitable for spectroscopy applications is extremely limited. State-of-the-art single-mode DFB lasers at 1.37 μm and 1.43pm have been fabricated for incorporation into spectroscopy instruments and are currently being used for atmospheric trace gas measurements in JPL's aircraft programs. The light against current characteristics of a DFB lasers at 1.43 μm under continuous operation is shown in Figure 1.

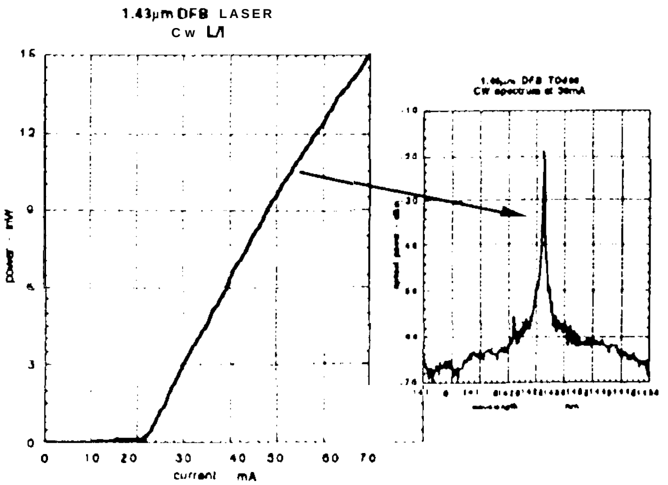

Fig 1. Continuous light output vs. current for a ridge waveguide laser.
Inset. Longitudinal mode spectra of the laser at 9 mw output power.

INGAAS/INP STRAINED QUANTUM WELL LASERS UP TO 2,06 μM

Compressively strained InGaAs quantum well structures on InP substrates have been used for the development of semiconductor lasers operating beyond 1.65 pm. In general, the InGaAs material wavelength increases with increasing the In composition and decreases under compressive strain and due to quantum size effects. The wavelength of the fundamental transition of strained InGaAs quantum well can be calculated using a finite square well potential. The calculated bandgap wavelength as a function of quantum well thickness at T=300°K, is shown in Figure 2. The dashed line in this figure shows the maximum bandgap wavelength achievable with various In compositions x without exceeding the critical thickness which was calculated on the basis of the force balance model proposed by Mathews and Blakeslee [1 1]. This calculation shows that the strained quantum well InGaAs on InP substrate may be used for lasers with emission wavelength in the range 1.65 to 2.1 pm.

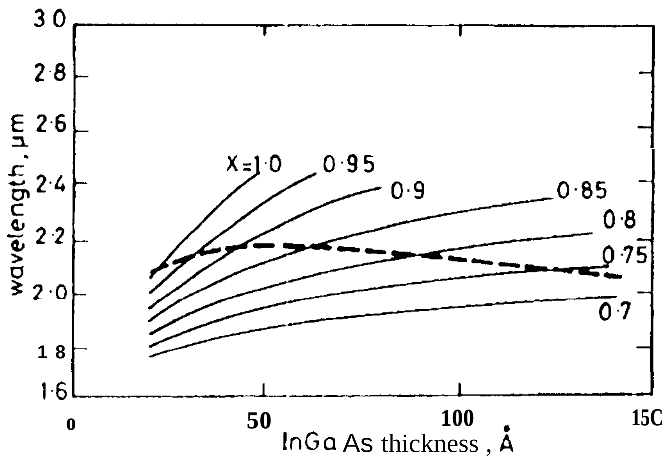

Fig. 2. Calculation of wavelength against thickness for compressive/y strained InxGa1-xAs compositions for x=().7 to 1.0 – limit orl critical thickness for strained layer,

We have previously reported the room temperature operation of InGaAs/InP quantum well lasers at wavelengths as long as 2.06 μm [12-13]. In general, to obtain low threshold current lasers, the confinement energy of the quantum well must be large enough to prevent carrier overflow. The electron confinement energy is defined as the energy difference between the sub-band edge of the well and the band edge of the barrier. Figure 3, shows a plot of the calculated electron confinement energy of

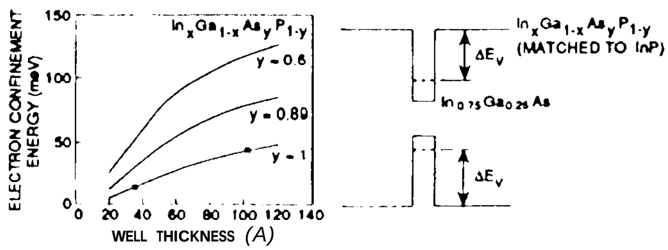

Fig 3 Plot of electron confinement energy of an In0.75 Ga0.25As strained quantum we// layer as a function of well thickness for several quaternary barriers

$In_{0.75}Ga_{0.25}As$ strained quantum well layers as a function of well thickness for several quaternary barriers. These results demonstrate that the higher the bandgap of the barrier layers the higher the electron confinement energy and therefore better laser performance. However, higher bandgap of the barrier layers will result in shorter wavelength emission for the lasers.

The light versus current characteristics of a typical 1 mm long laser under continuous operation (CW) at several temperatures are shown in Figure 4. Threshold currents as low as 30 mA and an external differential quantum efficiencies as high as 15% have been achieved. Attempts to increase the emission wavelength of InGaAs/InP quantum well lasers beyond 2.08 μm resulted in poor quality crystal growth with no luminescence emission from the wafers. It has been concluded experimentally that 2.06-2.07 μm is the longest wavelength that reliable InGaAs/InP quantum well lasers could be fabricated. The optical spectrum of an InGaAs/InP distributed feedback laser at 2.05 μm is shown in Figure 5. This is the longest wavelength DFB laser ever fabricated in this material system. Reliable DFB lasers at wavelength of 2.0465pm have been fabricated and used for the detection of the C02 isotopes.

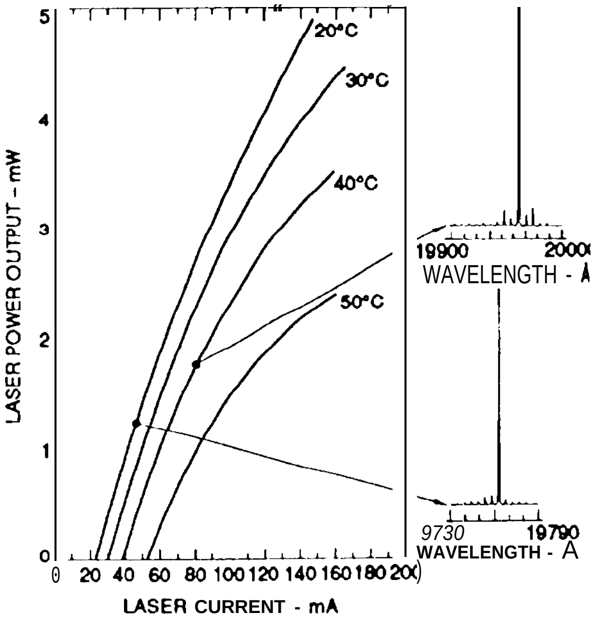

Fig. 4. Continuous light output against current for a ridgewaveguide laser at -2.0 μm at several temperatures.

MID-IR SEMICONDUCTOR LASERS

The III-V semiconductor lasers designed for mid-IR operation use various alloys and/or structures to achieve lasing. They include antimonide (Sb)-based type I and type II structures as well as InP- and Sb-based quantum cascade structures. Early work on type I lasers in the antimonide material system consisted of double heterostructures with bulk InGaAsSb active regions.

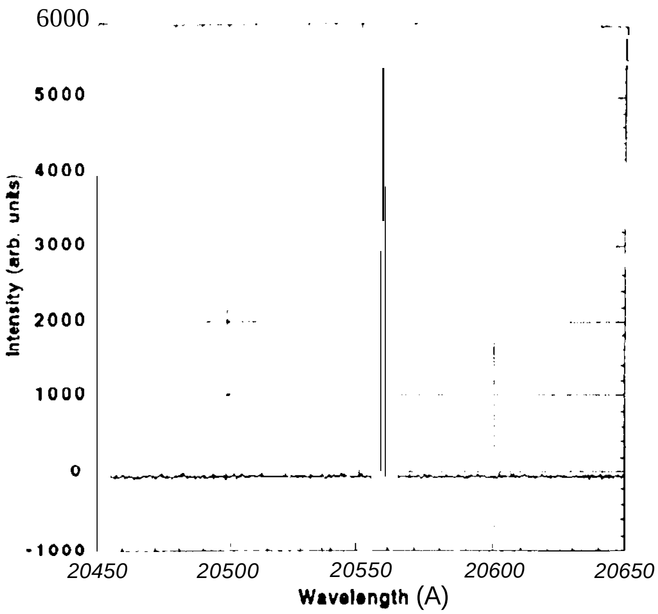

Fig. 5. Longitudinal mode spectra of a DFB laser at the temperature of 23°C.

However, marked improvement in the laser performance was achieved with the use of strained multi-quantum well laser structures. Room temperature operation of InGaAsSb/AlGaAsSb strained quantum well lasers has been demonstrated up to 2.15 μm [3]. The MBE-grown broad area devices had threshold current densities of 260 A/cm2, and CW output powers of approximately 190 mW per facet. By increasing the In and Sb content in the InGaAsSb quantum well, the emission wavelength was extended to almost 2.8μm [4]. The lasers operated under pulsed condition up to an operating temperature of 330K and under CW up to the maximum temperature of 234K. By employing InAsSb/InAlAsSb multi-quantum wells, emission wavelengths as long as 3.9 μm have been obtained with a CW operating temperature of up to 128K [5]. A primary limitation in the development of high temperature type-1 lasers is that the non-radiative Auger recombination process makes it increasingly difficult to achieve a population inversion at high temperatures when the bandgap is small.

In contrast to type-1 structures, calculations have predicted that Auger losses can be significantly suppressed in type-n superlattices and quantum wells. Additional advantages of a type II laser include longer operating wavelengths than the bandgap of each alloy, and larger offsets between energy bands. Disadvantages include a reduction in gain of the laser since the probability of an optical transition between conduction and valence band is smaller. Type II lasers employing InGaSb/InAs superlattices have been demonstrated, An electrically pumped type II MQW laser operating at 3.1 μm under pulsed conditions operated up to a temperature of 250 K [6]. A similar device employing AlSb barriers was optically pumped under pulsed conditions, and this device lased up to 285 K with a corresponding wavelength of 4 μm [7].

More recently, a type II superlattice laser with an operating wavelength of 5.2 μm was demonstrated to lase under pulsed optical excitation up to 185K [8]. However, while both electrically-pumped and optically-pumped type-II mid-IR lasers have been demonstrated, the results appear to yield high temperature Auger coefficients no better than values expected for bulk type-I structures with the same bandgap.

The quantum cascade (QC) laser utilizes the optical transitions between intersubbands and therefore permits a unipolar design in a staircase of coupled quantum wells to achieve lasing. This allows for one electron to produce as many photons as there are coupled quantum wells. This novel design has been demonstrated using both the InP-based and Sb-Based material systems. Using InAlAs/InGaAs quantum wells on InP substrates, quantum cascade lasers under pulsed operation at wavelengths from 4 to 10 μm have been demonstrated [9]. At wavelengths of 5 and 8.5 μm, room temperature pulsed operation has been demonstrated. Due to a low radiative efficiency leading to a high threshold current density (several kA/cm2) and substantial heating, CW operation has not yet been reported in this type of laser. To suppress the phonon relaxation responsible for this low radiative efficiency, a type II quantum cascade laser on GaSb was proposed and demonstrated. Another advantage of the type II QC laser, is its ability to operate at wavelengths shorter than its InP-based counterpart (<4μm). The demonstrated device operated in pulsed mode up to 120K at a wavelength of 3.8μm [1 O].

Although optimization of the laser structures and improvements in the epitaxial growth has gradually increased the operating temperature of semiconductor lasers in the 2-10 μm range, more research is necessary to achieve room temperature CW operation. Further more, for spectroscopy applications the lasers will need to operate in a single longitudinal mode which could be accomplished by integrating a ridge laser with DFB or DBR gratings or possibly by using an external fiber Bragg grating. Whatever the choice, much work is still to be done in fabricating these mid-IR single mode lasers.

APPLICATIONS

The Mars Volatiles and Climate Surveyor (MVACS) shown in Figure 6, is an integrated payload for Mars Surveyor Program (MSP) '98 lander mission. The payload consists of four major science instruments which include two cameras, a Meteorology package, and a Thermal and Evolved Gas Analyzer. The mast mounted Meteorology package includes pressure, wind, and temperature sensors, as well as a tunable diode laser sensor for accurately determining water vapor concentration of the surface atmosphere. The TDL sensor measures water vapor concentration by monitoring the level of absorption of a single vibration-rotation line within the 1.37 μm water vapor band. the laser wavelength is repetitively scanned over a very narrow spectral interval, which includes the absorption line of interest, by sweeping the laser current with the

Fig. 6 The Artistic presentation of Mars Volatiles and Climate Surveyor (M VACS) mission, Paige et. al. , to be launched as part of Mars Surveyor program.

laser operating temperature held fixed. The output beam is injected into a multi-pass Herriot type cell where two concave mirrors spaced 20 cm apart reflect the laser beam back and forth multiple times between distinctive spots on the mirrors. In such configuration the laser will produce 50 passes between the mirror, providing 10 meter optical absorption path capable of detecting surface concentrations better than one part per million. The Thermal and Evolved Gas Analyzer is designed to determine the concentrations of ices, adsorbed volatiles, and volatile bearing minerals in surface and subsurface samples acquired by the robotic arm also uses two tunable diode lasers at 1.37 μm and 2.04 μm. This is the first time that tunable diode lasers have been considered and will be used for planetary atmospheric studies.

In addition to the planetary applications, two JPL aircraft instruments designed for stratospheric measurements of water vapor at 1.37 μm and C02 at 1.43 μm have been built and flown aboard the NASA ER-2 and NCAR WB57F aircraft with excellent performance and reliability for the past two years.

Gas monitoring systems using TDLs is a fast growing area with a large commercial potential [14]. As an example, modern power plants use NH3 to reduce NOX emission from combustion processes. Accurate measurements and fast response times i. e. in-situ measurements during ongoing process, are of great Importance when power station has to fulfill environmental legislation and obtain cost efficiency. Other commercial application of considerable Interest are detection remote detection of methane and acetylene using the combination of TDLs and fiber optics.

SUMMARY AND CONCLUSION

The mature technology of near-IR 1.3 and 1.55 µm InGaAsP/In P diode lasers for fiberoptic communication has been extended to fabricate lasers that emit anywhere in the wavelength range of 1.1-2.06 µm. TDLs at the wavelengths of 1.37 µm, 1.43 pm, and 2.04 pm for the detection of water, carbon dioxide and their isotopes have been fabricated for planetary applications. It has been concluded experimentally that 2.06-2.07 µm is the longest wavelength that reliable InGaAs/InP quantum well lasers could be fabricated. Considerable progress has been made in the performance of Sb-based mid-IR semiconductor lasers in terms of maximum operating temperature and output power for emission in the 2-5 µm wavelength range. Although optimization of the laser structures and improvements in the epitaxial growth has gradually increased the operating temperature of semiconductor lasers, more research is necessary to achieve room temperature CW operation in single longitudinal mode for these lasers to be suitable for spectroscopy applications.

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