Low power consumption lasers for next generation miniature optical spectrometers for major constituent and trace gas analysis

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The air quality of any manned spacecraft needs to be continuously monitored in order to safeguard the health of the crew. Air quality monitoring grows in importance as mission duration increases. Due to the small size, low power draw, and performance reliability, semiconductor laser-based instruments are viable candidates for this purpose. The minimum instrument size requires lasers with emission wavelength coinciding with the absorption of the fundamental frequency of the target gases which are mostly in the 3.0-5.0 µm wavelength range. In this paper we report on our progress developing high wall plug efficiency type-I quantum-well GaSb-based diode lasers operating at room temperatures in the spectral region near 3.0-3.5 µm and quantum cascade (QC) lasers in the 4.0-5.0 µm range. These lasers will enable the development of miniature, low-power laser spectrometers for environmental monitoring of the spacecraft.

Nomenclature

FTIR	=	Fourier transform infrared spectrometer
QC	=	quantum cascade
MS	=	mass spectrometer
GC	=	gas chromatography
TLS	=	tunable laser spectrometer
IC	=	interband cascade

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DFB	=	distributed feedback
VCSEL	=	vertical cavity surface emitting laser

I. Introduction

A need exists for analyzers that can measure quality and trace contaminants in air on board spacecraft. Several types of instruments may be considered for continuous air quality monitoring within the space station.

a) Mass spectrometry (MS) is a very powerful analytical technique for the determination of the elemental composition of a sample or molecule.[1] The MS principle consists of ionizing chemical compounds to generate charged molecules or molecule fragments and measurement of their mass to charge ratio. The technique has the advantage of: high sensitivity analysis (ppb to ppt); multi molecular, quasi simultaneous analysis; moderately compact and robust instrument; and capable of isotopic analysis. The constraints for long duration space missions include: high power consumption; high vacuum (10^{-5} Torr or better); the requirement of waste gas disposal; and frequent calibration. A mass spectrometer (major constituent analyzer, MCA, developed by Hamilton Sundstrand and Boeing) has provided monitoring of six major atmospheric constituents (nitrogen (N_2), oxygen (O_2), hydrogen (H_2), carbon dioxide (CO_2), methane (CH_4), and water vapor (H_2O)) over seven years. These gases are sampled continuously and automatically via the ISS Sample Delivery System (SDS). Mass spectrometer experience has indicated that the operating life of the MS is limited by the operating life of the ion pump, which maintains the MS vacuum.

b) Fourier transform infrared spectrometery (FTIR) is another technique widely used in laboratory, environmental, and industrial quality control applications, and is a candidate for long duration space missions.[2] This type of spectrometer is based on the Michelson interferometer that use one stationary and one moving mirror. The combined beams interfere to produce time-varying beat patterns as the scanning mirror moves. The acquired waveform is an interferogram. A Fourier transformation is used to convert the interferogram into a spectrum. The drawback of an FTIR is its mechanical complexity. Such complex elements include moving optical elements which have to be guided with a very high precision over an extended distance, and very high alignment stability required for all optical components in the interferometer.

c) Gas chromatography (GC) is mostly used in analytical chemistry for separating and analyzing compounds that can be vaporized without decomposition.[1] Typical uses of GC include testing the purity of a particular substance or separating the different components of a mixture (the relative amounts of such components can also be determined). In gas chromatography, the *moving phase* (or "mobile phase") is a carrier gas, usually an inert gas such as helium, or nonreactive gas such as nitrogen The requirements for preparation and extraction of gas samples results in a long response time, which is incompatible with continuous monitoring.

d) Chemiluminescence is an indirect measurement technique that works on the principle of chemical reaction to cause conversion or light emission. The requirement of continuous calibration and maintenance is an undesirable feature of this technique for space.

e) Optical absorption spectroscopy or laser-based infrared spectroscopy is an efficient method of detecting various gas species in the atmosphere through optical interaction.[3] If the number of targets is small, the laser instrument has the potential to have the lowest mass and volume footprint of monitoring technologies,[4] and is therefore highly responsive to the requirements of long duration manned space missions. In order to achieve a minimal footprint instrument, it is necessary to employ a laser that emits at the fundamental absorption wavelength of the target gas.

Semiconductor lasers use the semiconductor bandgap in a quantum well diode configuration as the light generator. For laser spectroscopy applications, matching the laser wavelength to fundamental absorption modes of a target molecular species is critical to achieve high sensitivity in a compact form factor. Generally, these fundamental vibrational absorption modes are in the 3–12 µm range. However, the conventional materials used in diode lasers—primarily developed for telecom applications—are based on the GaAs and InP platforms; these lasers are unable to achieve lasing at wavelengths longer than about 2 µm. Using a pair of complementary technologies, we are working to cover the 3–12 µm wavelength range with low-input power laser sources suitable for spectroscopy applications. The first technology uses a quasi-conventional diode laser structure grown on GaSb with AlInGaAsSb cladding layers and InGaAsSb strained quantum wells. This technology is capable of covering the spectral range from 2 to >3.7 µm. The second technology is the quantum cascade (QC) laser, which uses alternating layers of InGaAs and AlInAs grown on InP to form multiple artificial optical transitions in a quantum well heterostructure. These QC lasers are capable of covering the spectral range from <3.8 to 12 µm.

A. 2.0-4.0 µm Type-I InGaAsSb Lasers

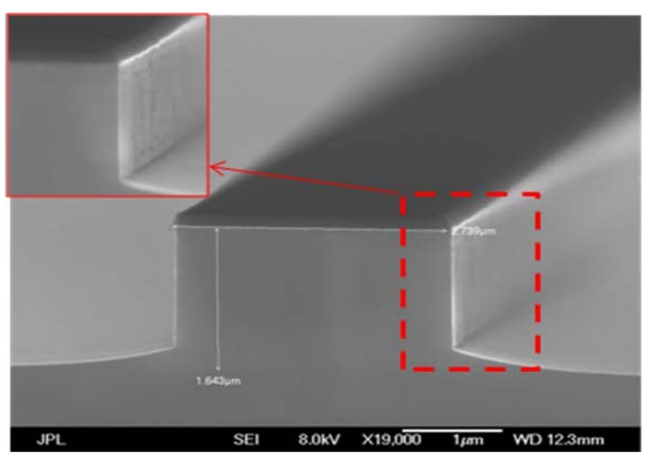
Many of the health hazard gases like hydrochloric acid, hydrogen fluoride, hydrogen bromide and formaldehydes have their fundamental absorption band in the 3-3.5 µm wavelength range. Until recently continuous wavelength (CW) room temperature operation of diode lasers was restricted to wavelengths below 2.7 µm due to the complexity of the expitaxial growth of the lasing material. To extend the operational wavelength beyond 2.7 µm, a new laser architecture based on interband cascade (IC) transitions was proposed and fabricated (Rui Yang while at JPL). IC lasers take advantage of band-gap alignment in Sb-based type-II quantum wells to reuse injected electrons in cascade stages for photon generation.[5] Although this laser were successfully delivered and integrated in the Tunable Laser Spectrometer (TLS) Instrument due for launch in 2011 to planet Mars, their operating performance was limited to a few milliwatts of optical power at the maximum operating temperature of 270 K due to several intrinsic limitations of the design.[6] The active area of IC lasers is usually comprised of many (6-10) cascades that results in high operational voltages typically exceeding 5V.

Moreover, to confine the lateral spreading of the current to a small area for low current and single mode operation, an IC laser is fabricated as a ridge waveguide device in which the laser active layer outside of the ridge is removed by the etching process. This process exposes the active layer of the laser at the sidewalls generating both a current leakage path and reliability concerns.

Fortunately, during the past few years major progress was made for extending the wavelength of diode lasers beyond 2.7 micron due to several breakthroughs in the epitaxial growth and bandgap design of GaSb-based lasers. The initial results clearly demonstrated that GaSb-based lasers operating in the 3.0-3.5 µm spectral range at room temperature and with low bias can be realized.[7,8] In addition, distributed feedback (DFB) lasers based on a lateral coupled grating design can be fabricated from demonstrated laser material. The laterally coupled DFB, in which a grating is created along the sides of a ridge structure, is a preferable fabrication technique for realization of single mode lasers. The entire fabrication of a laterally coupled DFB laser requires a single epitaxial growth and has been demonstrated at other wavelengths to have a much higher yield and reliability over the conventional DFB fabrication requiring as many as three epitaxial growths.

Device Fabrication

In collaboration with SUNY Stoney Brook, we are developing single frequency diode lasers in the 3.0-3.5 µm range.[9] The laser wafers were grown by solid-source molecular beam epitaxy using a VEECO GEN-930 reactor on Te-doped GaSb substrates. The details of the growth have been reported previously. After initial wafer characterization, narrow ridge waveguide lasers were fabricated using an inductively coupled plasma (ICP) reactive ion etching technique. Before dry etching the III-V material, a layer of PECVD (plasma enhanced chemical vapor deposition) silicon nitride was deposited, uniformly, on the surface. The silicon nitride etch mask was patterned with photolithography and etched in a parallel plate RIE system. The dry etching parameters were optimized such that the etching ratio (III-V to silicon nitride) is approximately 6. The profile angle of the etched ridges is approximately 90º and the smoothness of the ridge sidewalls is on the order of nanometers. Figure 1 is an SEM image of a 3 µm ridge laser with an inset SEM image that targets the sidewall of this ridge at a magnification of 33,000x.



After dry etching the wafer, a thick layer of silicon nitride was deposited on the surface in order to lower waveguide optical loss arising from the overlap of the optical mode with the top metal contact. Figure 2 is an SEM image of a 3 μm wide laser ridge that was covered by approximately 8000 Å of PECVD silicon nitride. Again using photolithography, a narrow stripe opening was patterned on top of the laser ridge and then dry etched to expose the GaSb cap. A Ti/Pt/Au metal contact pad was evaporated on top of the ridges, and thick electroplated Au was deposited on the top of the device to improve heat dissipation. Next, the wafer was thinned to approximately 100 µm by mechanical lapping and a bottom Ti/Pt/Au metal contact was deposited by E-beam evaporation. Finally, the wafer was cleaved into 1 mm x 2 mm bars that were mounted junction side-up on copper mounts with In solder. Figure 3 shows an SEM image of a fabricated 8 µm laser ridge.

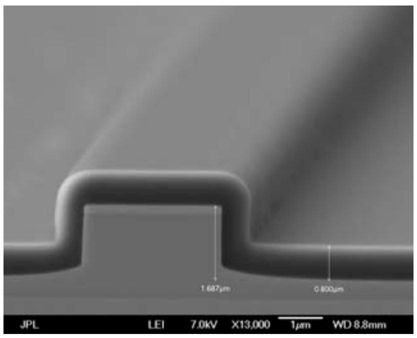


Fig. 2 An SEM image of a 3 µm laser ridge coated with 8000Å of PECVD silicon nitride

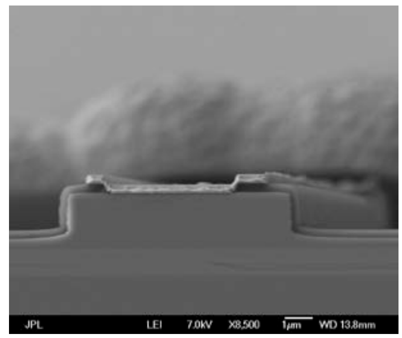


Fig. 3. An SEM image of completely fabricated 8 µm ridge waveguide laser ready for testing.

Figure 4 shows the light-current-voltage characteristics of a 5 µm x 2.5 mm ridge waveguide laser in the temperature range from -3 ºC to 47 ºC. At ambient temperature, the laser generates above 4 mW of CW power and the laser threshold current is I_{th}= 120 mA. The laser power consumption is P_e = 0.08 W and the power consumption is only 0.15W when the laser output power reaches P_o = 1mW (the optical power required for typical spectroscopic measurements using tunable laser spectrometer instruments). Higher optical power, necessary for photoacoustic spectroscopy techniques can be achieved by operating the laser at lower temperatures. Output power levels above 10 mW can be readily achieved in these devices by operating the device at temperatures using a thermo-electric cooler.

The developed lasers operate in CW mode up to max temperature of 60 ºC, and the emission wavelength at this temperature is λ = 3.2 µm (Fig. 5); At T = 17 ºC, the wavelength λ = 3.1 µm. The emission wavelength was set by the laser design and can be extended to λ = 3.5 µm without significant degradation in the laser performance. Extension of operating wavelength to 3.27 µm will enable their use for methane detection so these devices can replace Interband Cascade (IC) lasers that are currently used.

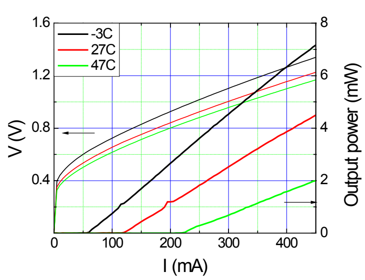


Fig. 4 CW light-current-voltage characteristics of A 5 µm x 2.5 mm ridge waveguide laser in A temperature range from -3 to 47 ºC

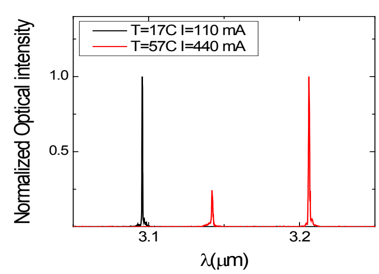


Fig. 5 the spectra of long wavelength type-I laser

Compared to IC lasers, the current GaSb-based lasers have much higher operational temperature and lower power consumption (Fig. 6). Their performance is close to the performance of commercially available Nanoplus diode lasers operating at shorter wavelength and used for water detection in tunable laser spectrometers.

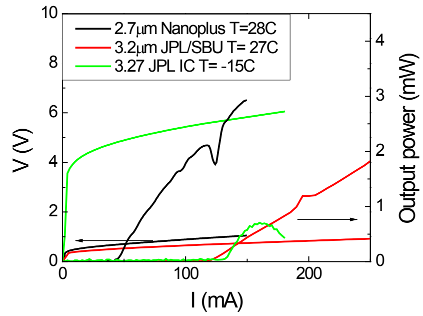


Fig. 6 CW light-current-voltage characteristics of mid-IR lasers
Comparison of the current work with the interband cascade lasers at 3.2 µm

B. 4.0-5.0 µm Low Input Power Quantum Cascade Lasers

Performance from QC lasers has improved substantially over the past several years. From wall-plug efficiencies in the few percent range at best in 2004 (Ref. 10), we have now seen wall-plug efficiencies exceeding 12% in continuous operation mode at room temperature[11], and wall-plug efficiencies exceeding 50% in pulsed mode operation at low temperatures.[12,13] While these lasers are capable of emitting a substantial amount of output power, they also require a large input power—for example, >1.5 W emission for >18 W of input in Ref. 10. Thus, to operate the laser, a thermal management system capable of dissipating ~17 W of heat is required. Laser systems of this nature are impractical for most laser spectroscopy applications.

We should recognize that "high performance" to date has been interpreted to mean high output power and/or high wall-plug efficiencies. If we are willing to relax both of those requirements, we can design "high performance" lasers that operate with minimal amounts of input power.

To reduce input power, we look at the constituents of voltage and current to QC laser operation. There are a number of ways by which we can effectively reduce operating voltage V, which is simply the number of QC active–injector region periods N_p within the QC active core multiplied by the total voltage drop per period.

$$V = N_p \bullet q(E_{ph} + \Delta)$$

With q as the electron charge, the total energy drop in each QC period is simply the energy of the photon transition E_{ph} along with the defect energy Δ. In effect, Δ is "what's left over" after the electron energy falls by a photon; more specifically, Δ includes enough energy drop for phonon depopulation of the lower laser state and the prevention of thermal backfilling into the lower laser state. While the photon energy is fixed for any particular application, we have design control over both N_p and Δ. Thus, both can theoretically be decreased in order to decrease laser operating voltage.

The other element we are able to consider is operating current, or more specifically here threshold current I_{th}. The condition for laser threshold is that optical gain equal optical loss, and thus for a QC laser one derives

$$I_{th} = \frac{\alpha_m + \alpha_w}{N_p \Gamma g_c}(d \times w \times L)$$

where α_m is the mirror loss, α_w is the waveguide loss, Γ is the confinement factor of the active core, and g_c is the per-period gain coefficient. The spatial dimensions w and L are the width and length over which the device is electrically pumped while d is thickness of the active core. From our discussion about N_p, we can see that decreasing N_p will have the negative effect of increasing I_{th}. To further complicate the analysis, in minimizing I_{th} we ideally wish to minimize the area over which the laser is electrically pumped, namely w and L. However, as α_m is a function of L, decreasing L decreases α_m and in turn contributes again to an increase in I_{th}. Since laser operation fundamentally implies reaching threshold, we are left with an optimization problem. One capability that is now useful to exercise, especially since the requirement of ultra-high output power has been relaxed, is the ability to increase the as-cleaved laser facet reflectivity through facet coatings. In a sense, we are now approaching the operating regime of VCSELs; that is, we want to minimize the cavity size (w and L) while using cavity mirrors that are highly reflective to hold threshold current at an operable level.

II. Conclusion

Efficient semiconductor lasers in the 2-12 µm wavelength range are being developed and will be available in the near future. These lasers will enable the development of miniature, low-power laser spectrometers for environmental monitoring of the spacecraft. These lasers will enable the development of miniature, low-power laser spectrometers for environmental monitoring of the spacecraft.

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